Wave Computations for Microwave Education

Scott W. Wedge, *Member, IEEE,* and David B. Rutledge, *Senior Member, IEEE*

Abstract— **The analysis of even simple microwave circuits can involve complicated calculations. Students repeatedly forced through this exercise are left exhausted, and never develop understanding and insight into the principles of high-frequency circuit design. The use of computer-aided design software eliminates the network analysis burden, but it is a precarious solution: students easily become dependent on software and never develop analytical analysis skills. Discussed here is a simple wave computational approach to microwave network analysis. The method is derived from Mason's theory of signal flow graphs and is based on wave variables and scattering parameters. The approach is easily understood and applied as either an analytical analysis tool, or within a microwave CAD analysis engine. PC software using this computational technique is described and its educational applications are discussed.**

I. INTRODUCTION

MANY concepts in high-frequency circuit design are difficult for students to grasp. Transmission-line theory is rarely met with enthusiasm and the often onerous mathematics of microwave network analysis can be discouraging. Most students are intimately familiar with Kirchhoff's laws, but the dramatic spatial variations in branch current and node voltage in high-frequency circuits reduces the relevance of these axioms. Microwave networks are best represented by the complex scattering parameters, also known as s-parameters. These represent the ratios of incident and scattered traveling waves and are one of the few measurable quantities at microwave frequencies. Discussed here is a simple educational approach to microwave network analysis using these wave based parameters. The approach emphasizes the understanding of traveling wave variables, develops student analytical s-parameter calculation skills, and provides insight into microwave CAD computation techniques.

Stimulating the development of analytical skills requires wave substitutes for Kirchhoff's easily applied laws. These come in the form of wave equivalence rules from *linear connection theory*. The resulting network interpretation in terms of components and connections increases student sensitivity to microwave measurement problems. This approach also leads to the use of signal flow graph theory for microwave network analysis. Signal flow graphs are helpful in developing the students' understanding of wave phenomena, and with practice, give them the ability to solve some network analysis problems by inspection.

Students with access to computer-aided design software can study complex circuits, get a feeling for the magnitudes of circuit quantities, learn to what extent a network is sensitive to its components, and compare theoretical models with laboratory results. The danger, however, is the ease with which students become dependent on software. The dependent student will rarely understand the software's analysis algorithm, and still forgo learning any analytical analysis techniques. Software used for educational purposes must therefore be used judiciously. Its analysis algorithm should be simple and disclosed to the students. To foster a balance between analytical skills and computational tools, students should be able to apply the same algorithm in hand calculations. Educational CAD software should not be intimidating; it should provide a quick, friendly, and painless means of accomplishing network analysis, leaving time to develop student insight and intuition. Discussed here is a microwave CAD program developed at Caltech to meet these requirements.

The fundamentals of wave analysis using linear connection theory are discussed in Section II leading to the derivation of wave computations from signal flow graphs. Described in Section III is educational computer-aided design software developed at Caltech that uses this wave computational technique. Section IV briefly describes how this software is applied in Caltech's microwave engineering course.

II. LINEAR CONNECTION THEORY

As in any network analysis approach, a network's response is found from knowledge of its components and its topology. Linear connection theory is the interpretation of a circuit's topology in terms of a collection of *connections*. In the general black-box network analysis problem, illustrated in Fig. 1(a), a group of components $S_1, S_2, \cdots, S_m$, have been combined to form an aggregate network $\boldsymbol{S}'$. The small circles that separate the components represent connections. The detail at a single connection is shown in Fig. 1(b). A connection forms a *reference plane* boundary between any two components; it marks the point where one component ends and another begins. A connection differs from a node. Any number of components may share a node, but only two can share a connection. The connection interpretation is quite practical. A microwave circuit cannot be probed. Students must understand that getting input and output to and from a microwave component or circuit, even for measurement purposes, is only done by connecting to its external ports.

In the wave variable approach, network characterization is accomplished using scattering matrices. Associated with each multiport scattering matrix $\boldsymbol{S}$ is an input wave vector $\boldsymbol{a}$ and scattered wave vector $\boldsymbol{b}$ satisfying $\boldsymbol{b} = \boldsymbol{S}\boldsymbol{a}$. At a connection,

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S. W. Wedge was with the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91109. He is now with the Department of Research and Development, EEsof Inc., Westlake Village, CA 91362.

D. B. Rutledge is with the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91125.

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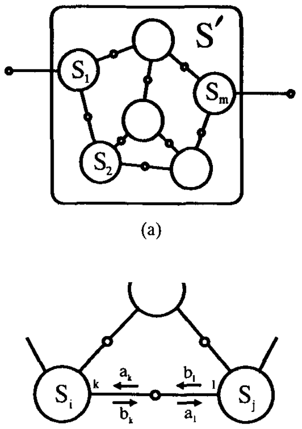


(a)

(b)

Fig. 1. An aggregate network, S', consisting of many interconnected components, each characterized by scattering parameters. Schematic diagram of the network (a), and detail showing an incident and output wave for components S_i and S_j at a connection (b).

simple constraints are imposed on the wave variables present. Where a connection exists there will be an equality established between incident and scattered waves known as the *connection law.* The connection law applied to Fig. 1(b) gives

$$a_k = b_l \qquad a_l = b_k. \tag{1}$$

The objective of microwave network analysis is to determine the overall scattering matrix of an aggregate network from the scattering matrices of its components. The derivation and calculation of component scattering matrices is straightforward [1]. The network analysis is generally carried out through a series of matrix calculations [2] that involve separating the internal and external variables of the network to prevent an unnecessary calculation of the insignificant parameters [3]. The matrices tend to be large and sparse and specific computational techniques for the microwave matrix equations have been described elsewhere [4], [5].

Spending class time to discuss sparse matrix solution techniques becomes an unwarranted departure from microwave network theory. The dilemma is how to develop a reasonable analytical capability in the student without too much dependence on CAD tools; and if possible, to develop complementary methods for both. Salvation comes in the form of Mason's theory of signal flow graphs [6]. Historically, signal flow graphs have been extremely valuable in control theory. They have made less of an impact in circuit theory since the graphs are frequently more complicated than circuit diagrams. This is not the case with microwave circuits. Traveling waves and scattering matrices have convenient signal flow graph representations. The graphs also give physical insight by clearly showing the contributions to wave scattering that occur in a circuit. Signal flow graphs are useful in demonstrating circuit effects, in explaining computer-aided design algorithms, and in helping students understand microwave measurement calibration and error-correction schemes.

Signal flow graph notation and definitions can be taken directly from Mason's original paper [6]. In a microwave signal flow graph the wave variables become *nodes* and the scattering parameters become the *branches* that connect the nodes. It is the *gain* between nodes that is an important microwave parameter; it is one of the few measurable quantities. Our students are taught to use Mason's general rule to solve for gain, written as a sum over each of the paths from the input node to the output node:

$$G = \sum_k G_k \frac{\Delta_k}{\Delta} \tag{2}$$

where G_k is the gain of path$k$, Δ_k is the cofactor of path k, and Δ is the determinant of the graph, given by

$$\Delta = 1 - \sum_m P_{m1} + \sum_m P_{m2} - \sum_m P_{m3} + \cdots. \tag{3}$$

Here P_{mr} is the gain product of the mth possible combination of r nontouching loops. Cofactor Δ_k is the determinant of the loops that do not touch path k.

Mason's formula applied to microwave network analysis may be demonstrated with two significant examples. The first concerns the reduction of a multiport network by the connection of two of its ports. Shown in Fig. 2 is the reference connection diagram and corresponding signal flow graph for a network *intraconnection.* In the figure, port l is connected to port l on network $\boldsymbol{S}$ to form new network $\boldsymbol{S}'$. The flow graph is formed using connection law (1) and the pertinent scattering parameters. The graph has three loops on the right. Two are self loops with gain s_{kl} and s_{lk} and the other has gain $s_{kk}s_{ll}$. The first sum in the determinant is just the sum of the three loop gains. The second is the sum over all the pairs of loops that do not touch each other. Only the two self loops do not touch. The graph determinant is therefore

$$\Delta = 1 - (s_{kl} + s_{lk} + s_{kk}s_{ll}) + s_{kl}s_{lk} \tag{4}$$

which can be simplified to

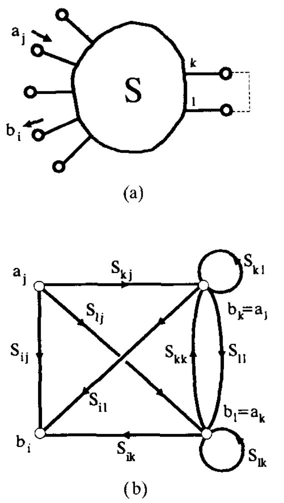
$$\Delta = (1 - s_{kl})(1 - s_{lk}) - s_{kk}s_{ll}. \tag{5}$$

There are five paths from a_j to b_i. The path gains and their cofactors are listed in Table I. Applying Mason's rule yields the new scattering parameter s'_{ij}

$$s'_{ij} = s_{ij} + \frac{s_{kj}s_{il}(1 - s_{lk}) + s_{lj}s_{ik}(1 - s_{kl}) + s_{kj}s_{ll}s_{ik} + s_{lj}s_{kk}s_{il}}{(1 - s_{kl})(1 - s_{lk}) - s_{kk}s_{ll}}. \tag{6}$$

As apparent in Fig. 2(a), the same signal flow graph may be used despite the number of ports possessed by the network being reduced. Indexes k and l denote the ports being reduced by the intraconnection. Indexes i and j denote any two other ports possessed by multiport $\boldsymbol{S}$ and may be varied over all other ports to generate a new scattering matrix.

A second signal flow graph application is in the solution of a network *interconnection.* Given in Fig. 3 is the reference diagram and corresponding signal flow graph for this case. Here a connection joins ports of two networks to form a single network. Indexes k and l again denote the ports being joined. Once again, connection law (1) and the pertinent scattering parameters are used to form the graph. Indexes i, j, and m denote other ports possessed by $\boldsymbol{S}$ and $\boldsymbol{T}$ that are effected by



(a)

(b)

Fig. 2. Reference connection diagram (a) and signal flow graph (b) for a network intraconnection. The network S is an arbitrary multiport with indexes i and j denoting any two ports other than the joined ports k and l.

TABLE I
PATH GAINS G_k AND COFACTORS Δ_k FOR A NETWORK INTRACONNECTION.

G_k	Δ_k
s_{ij}	Δ
$s_{kj}s_{il}$	$1 - s_{lk}$
$s_{lj}s_{ik}$	$1 - s_{kl}$
$s_{kj}s_{ll}s_{ik}$	1
$s_{lj}s_{kk}s_{il}$	1

the connection. Solving the signal flow graph gives

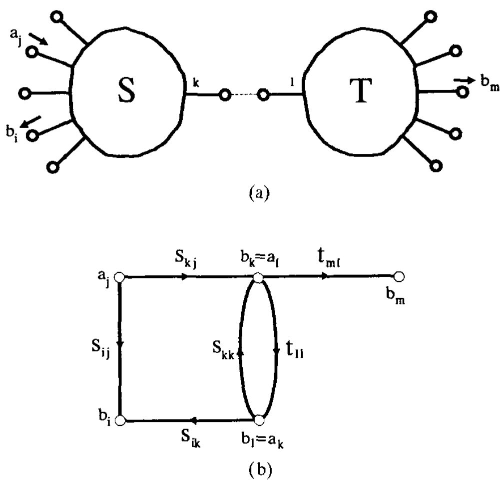
$$s'_{ij} = s_{ij} + \frac{s_{kj}t_{ll}s_{ik}}{1 - s_{kk}t_{ll}} \tag{7}$$

$$s'_{mj} = \frac{s_{kj}t_{ml}}{1 - s_{kk}t_{ll}}. \tag{8}$$

As before, the indexes may be varied over all ports other than k and l to find the complete scattering matrix of the resulting network.

III. COMPUTER-AIDED DESIGN

The significance of *connection equations* (6)–(8) extends beyond analytical network analysis. The intra and interconnections of Figs. 2 and 3 are the only two basic types of connections needed to solve the complete black-box network analysis problem presented in Fig. 1. A CAD algorithm, known as *subnetwork growth* [1], involves the repeated application of such connection equations. This simple and efficient analysis technique proceeds by building up a large network by repeatedly connecting smaller subnetworks together, two at a time. Equations (6)–(8) represent the simplest form of subnetwork growth in which a single connection is analyzed at a time. Compared to matrix analysis methods that involve the inversion of one large sparse matrix, the subnetwork growth procedure involves multiple inversions of a 2-by-2 dense matrix. The procedure has been studied by Monaco and Tiberio [7] and Filipsson [8]. Computation time is sensitive to the order in which the connections are processed, so a search for the connection that results in a new subnetwork with the smallest number of parameters is needed.



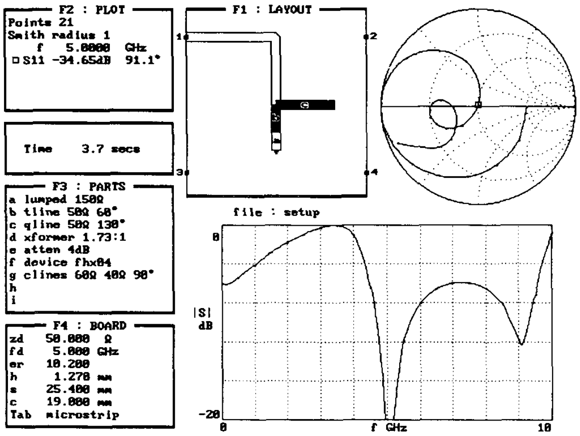
(a)

(b)

Fig. 3. Reference connection diagram (a) and signal flow graph (b) for a network interconnection. Networks S and T are arbitrary multiports with indexes i, j, and m denoting any two ports other than the joined ports k and l.

A subnetwork growth algorithm, using connection equations (6)–(8), has been implemented in an educational PC computer-aided design program developed at Caltech. The program, named PUFF [9], combines component level scattering parameter calculations with these connection equations to form a powerful microwave CAD capability. Linked lists are used to monitor the components and their connections. To perform a network analysis, PUFF collapses the lists by repeatedly forming intermediate subnetworks through intra and interconnections until the final network remains. The program is optimized for IBM compatible personal computers and has a simple-to-use interactive schematic-capture interface. An example VGA screen dump of the PUFF display is shown in Fig. 4. Circuits are constructed in the *Layout* window (top center) using cursor keys. The distributed components are drawn to scale. Substrate parameters entered in the *Board* window (lower left) determine the layout dimensions and drawing scale. Components are specified in the *Parts* window. The *Plot* window (upper left) is used to identify scattering parameters to be plotted on the Smith chart and rectangular plots. The parameters are numbered based on connections to either of the four external ports in the *Layout* window.

PUFF performs linear swept-frequency analyses of microstrip and stripline networks. The program's component library includes lumped elements, transmission lines, coupled transmission lines, attenuators, and transformers. Distributed elements can be analyzed with ideal models, or with advanced models that include the effects of losses and dispersion. PUFF can load s-parameter files that contain transistor data or parameters that represent idealized meters or sources. This also permits microwave measurement data to be loaded into the program for a side-by-side comparison of theory and experiment. PUFF internally generates the s-parameters for tees and crosses, needed when more than two elements are connected at a common point, and for open circuits and



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F2 : PLOT
Points 21
Smith radius 1
   f   5.0000  GHz
□S11 -34.65dB  91.1°

Time    3.7 secs

F3 : PARTS
a lumped 150Ω
b tline 50Ω 60°
c qline 50Ω 130°
d xformer 1.73:1
e atten 4dB
f device fhx04
g clines 60Ω 40Ω 90°
h
i

F4 : BOARD
zd   50.000  Ω
fd    5.000 GHz
er   10.200
h     1.270 mm
s    25.400 mm
c    19.000 mm
Tab  microstrip

F1 : LAYOUT

file : setup
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Fig. 4. A VGA screen dump of the PUFF display for a shunt-stub matching circuit.

grounds. No optimization routines are included in PUFF, as they tend to be abused by students. Instead, the analysis algorithm has been made fast enough to allow students to optimize the circuits themselves while learning the effects of subtle component changes. To assist in the study of time-domain reflectometry, PUFF can also compute step and impulse responses. For laboratory support, PUFF has the ability to generate camera-ready artwork for fabrication of microstrip and stripline circuits.

IV. MICROWAVE EDUCATION AT CALTECH

In the microwave circuits course at Caltech a great deal of emphasis is placed on the laboratory. The wave computation techniques described here and presented in the course lecture material are intended to help predict and explain effects seen in the laboratory. Each week students use PUFF to design, fabricate, and measure a new microwave integrated circuit. Over the duration of the course, each student generates a minimum of eight circuits including matching networks, low-pass and band-pass filters, directional couplers, amplifiers, and oscillators. The students arrive for each experiment with a completed circuit design, and then use PUFF to produce photographic artwork on an HP LaserJet printer. The artwork is photographically reduced onto 2.5$''$ square glass emulsion plates. These are developed and used as masks to expose photoresist covered, copper clad *Duroid* substrates. After etching, the fabricated circuits are placed in a brass text fixture and measured with a microwave network analyzer. The measured s-parameters are placed into a file readable by PUFF. The students then compare PUFF's predictions alongside their measured data. Correlation between the two is usually not perfect, so the students must determine where the analysis goes wrong. PUFF does not automatically compensate for losses and discontinuities, and it is a good puzzle for the students to adjust their circuit models to include these effects.

Students learn the principles of high-frequency design best through the construction of many simple circuits that each demonstrate certain effects. Quarter-wave low-pass filters, for example, are useful in studying open-circuit end-effects in low-impedance transmission-lines and periodicity in the frequency domain. Branch-line and rat-race couplers are interesting examples of symmetrical four-port structures and are good for examining tee discontinuities. Simple amplifier and oscillator circuits demonstrate many aspects: the DC and AC performance of microwave transistors, matching circuit design, feedback, noise performance, resonant circuits, and injection locking.

V. CONCLUSION

Wave computation methods based on scattering parameters and signal flow graphs help simplify the often complicated calculations of microwave circuit theory. They give students a practical analytical network analysis capability and help develop insight into microwave circuit physics. A collection of simple wave computations are all that is needed to provide a powerful microwave computer-aided design capability. An educational microwave CAD program, named PUFF, has been developed using this approach, and includes many features to assist with microwave education [10].

Based on the results obtained at Caltech, and the feedback received from elsewhere, PUFF has proven to be a useful tool for teaching microwave circuit theory. The PUFF program[1] has been in distribution since 1987, and has over 10,000 student and professional users worldwide.

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[1] Packages containing the 60 page manual and diskette are provided for \$10 each. Direct PUFF requests to: Puff Distribution, Electrical Engineering M/S 116-81, California Institute of Technology, Pasadena, CA 91125.

Scott W. Wedge (S'82–M'85–S'87–M'90) received the B.S. degree from the California State Polytechnic University, Pomona, in 1983, the M.S. degree from the University of Illinois in 1986, and the Ph.D. from the California Institute of Technology, Pasadena, in 1991, all in electrical engineering.

From 1983 to 1991 he was with Hughes Aircraft Company, Ground Systems Group, Fullerton, CA, and is now with EEsof, Westlake Village, CA. His interests and experience from industry and academia include RF and MMIC circuit design, computational electromagnetics, microwave measurement systems, and high-frequency CAD.

Dr. Wedge is a member of Tau Beta Phi and Eta Kappa Nu, a registered professional engineer in California, and was a Hughes Doctoral Fellow at Caltech. He is coauthor of the educational microwave CAD program, *PUFF*, which has over 10,000 users worldwide.

David B. Rutledge (M'75–M'77–S'78–M'80–SM'89) received the B.A. degree in mathematics from Williams College, Williamstown, MA, in 1973, the M.A. degree in electrical sciences from Cambridge University, Cambridge, England, in 1975, and the Ph.D. degree in electrical engineering from the University of California at Berkeley, in 1980.

In 1980 he joined the faculty at the California Institute of Technology, Pasadena, where he is now Professor of Electrical Engineering. His research is in developing millimeter and submillimeter-wave monolithic integrated circuits and applications, and in software for computer-aided design and measurement. He is coauthor of the CAD program, *PUFF*, which has over 10,000 users worldwide.

A Hands-On Practical Approach to Teaching Engineering Design

S.M. Miri, *Member, IEEE,* and R.J. Fu

Abstract—**A hands-on practical approach to teaching design in engineering courses is presented. This approach is based on the philosophy that students learn the fundamental laws and their applications to design most effectively through design practices which result in demonstrated success. Through such practice, they learn that success in engineering requires understanding the fundamentals and attention to details, they learn the science/art of the iterative design process, and they gain a great deal of self confidence. Students must learn that to be innovative means having a deep understanding of fundamentals and being able to work out details, and that nothing, not even computers, can replace these two ingredients of excellence.**

I. INTRODUCTION

To prepare the engineering graduates for the challenges of today's very competitive industrial world, we must provide them with a strong foundation upon which they could build further engineering knowledge on their own. Such a foundation consists of a deep understanding of the fundamentals of engineering and the ability to deal with the degree of details required in developing new technologies and competitive products. Today, too many engineering students believe they can get by without understanding the fundamentals, and without paying attention to details. To change this attitude, we must demonstrate to them the necessity of having a deep understanding of fundamentals and of being able to work out "tedious" details in order to be innovative and succeed as engineers. An approach to teaching design is presented in this paper which, we believe, can change the students' attitudes about learning fundamentals and dealing with details, and thus, can help produce future engineers who will be more innovative than many of today's practicing engineers.

II. THE TEACHING PROCESS

A. Selecting a Suitable Design Project

The first step in planning is to select a suitable design project. Careful attention must be paid in selecting the design project if we are to make the design experience a meaningful one for the students. A design project can be considered to be suitable for the proposed teaching approach if a) the instructor has completely worked out the design beforehand; either in conjunction with a previous research project or just for the sake of the class, b) it is relevant to the course material, c) it can be done by the students in a relatively short period of time, d) a prototype can be built or ordered, inexpensively, before the end of the semester/quarter, and e) all the required manufacturer's catalogues can be made available.

Our experience with the proposed teaching approach has been in a senior level required course on electromagnetic devices offered in the Electrical Engineering Department. Usually, this class has an average of forty students. The design project discussed in the following section was assigned as the first take-home test and the students were given nine days to complete the project. All students were given the same design project.

B. The Design Specifications

The design requirements should be specified unambiguously. In the professional world, the design requirements are seldom unambiguous and it is left to the engineer to

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The authors are with the Department of Electrical Engineering, University of North Carolina at Charlotte, Charlotte, NC 28223.

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