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FOREWORD

The Circuit Theory Symposium was conceived as a major forum for the interchange of important research results in our field. The response of the Circuit Theory community has been enthusiastic and the quality of papers submitted has been exceptionally high. This digest comprises summaries of all accepted papers and the texts of all contributed papers will appear in the Transactions. The Symposium is obviously successful beyond all expectations.

The success of the Symposium is, in large measure, due to the unstinting efforts of the Technical Program Committee in reviewing the contributed papers as well as in organizing special sessions of invited papers. On behalf of the Circuit Theory Group and the Symposium Committee, I would like to express special thanks to the members of the Program Committee. My thanks also go to many of my friends and colleagues who have helped in planning and organizing the Technical Program for the Symposium.

Bharat Kinariwala
Chairman,
Technical Program Committee

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AUTOMATED NETWORK DESIGN: THE FREQUENCY DOMAIN CASE

S. W. Director*
University of Florida

R. A. Rohrer*
Fairchild Semiconductors

An automated network design principle of far reaching consequences, is shown to rely on the ability to measure, effectively and efficiently, the "sensitivity" of well chosen indices of network performance with respect to all possible network parameters--including topology. Application of Tellegen's theorem to an originally specified network leads to a simple computation of the unnormalized sensitivity of any associated network function with respect to all pertinent network parameters in terms of analysis of it and its topologically equivalent adjoint network. The reinterpretation of this sensitivity to scalar indices of network performance leads to an automated frequency domain network design algorithm.

A computer program has been written to implement the iterative design algorithm and has been applied to several practical problems. The effectiveness of this program is demonstrated by a wide-band amplifier design example.

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*Formerly with University of California, Berkeley.

Research sponsored by the National Science Foundation under Grant GK-2277 and the Air Force Office of Scientific Research under Grant AF-AROSR-1219-67.

Session 1, Paper 1.2

AN ITERATIVE METHOD OF NETWORK ANALYSIS

M. F. Moad
Georgia Institute of Technology

A method of analysis characterized by an exceedingly low number of independent variables is introduced. With this method, it is possible to analyze many netowrks by using only one or two independent variables regardless of the number of branches or nodes. It is also possible to calculate immitances, transfer functions, n-terminal parameters, and N-port parameters with ease. The advantages of this method over many others can be more appreciated when the network involves ideal transformers, independent sources in elementless branches, controlled sources, nonlinear elements, etc.

The method is based on the simple idea of scanning the whole network iteratively, one branch at a time. At each step all the independent equations concerning the branch at hand and the previous branches are written. When the last branch is reached, sufficient equations to solve for all the variables of the network become available.

An approach to iterative network design, based on the method, is also discussed. With this approach, it is possible to build a network of any size with known responses in a relatively short time.

The method could be used advantageously in computer-aided circuit design.

Session 1, Paper 1.3*

LEAST p^{th} APPROXIMATION: THEORY AND APPLICATION

Gabor C. Temes and Yook Fung Zai
Ampex Corporation

The iterative optimization of circuits or systems in a prescribed frequency and/or time range usually requires that a single quantity be defined as error-criterion. In this paper the difference between required and actual performance, weighted, raised to the p^{th} power and summed over the frequency/time range of interest, is chosen as this criterion. Selecting p as an even number greater than 2, the maximum error in the range tends to become considerably smaller than for least-squares optimization. This choice also leads to a novel method of optimization which has superior convergence properties and which usus an algorithm only slightly more complicated than least-squares techniques. For p=2, the process degenerates into the classical Gauss-Newton method.

If necessary, the convergence of the iteration may be insured by using straightforward damping procedures, separately or in combination.

Two illustrative examples are included to show the convergence properties of the process in both the frequency- and time-domain.

Session 1, Paper 1.4*

DIGITAL FILTERS WITH EQUIRIPPLE PASSBANDS

A. G. Constantinides
The City University, London

A method of synthesis of digital filters having equiripple passbands and arbitrarily defined stopbands, is given in this paper.

The method rests on a transformation which is parallel to that of continuous filters. A general form for the amplitude characteristic of digital filters is obtained and it is shown that Chebyshev and Elliptic digital filters are essentially special cases of this general amplitude characteristic.

Session 1, Paper 1.5*

COMPUTER ANALYSIS OF CONSTRAINED NETWORKS

Sanjit K. Mitra
University of California, Davis

Presently, several general purpose digital computer programs are available for dc and ac analysis of networks. A major limitation of these programs arises in the case of active netowrk analysis due to their inability in handling any other ideal active elements but voltage controlled current source.

In this communication, a simple scheme is proposed which allows the modification of presently available computer programs to enable them to treat all types of active elements. The method is based on the addition of positive and negative parasitic elements at appropriate places to create additional node. Some of the parasitic elements are then absorbed by the ideal active device and the active device so modified may be described by short-circuit parameters. A table of such equivalent circuits of some commonly used 3-terminal active devices is included.

Another active element which is not a standard element in any network analysis program is the ideal operational amplifier. Two simple "exact" equivalent circuits of the two types of operational amplifiers using current-controlled current sources are proposed. These equivalent circuits are easily adaptable for computer-aided analysis by making use of the scheme suggested above.

The suggested method has been used to modify Calahan's computer analysis program (CIRAN), which is being used successfully.

Session 1, Paper 1.6*

A "TEXTBOOK" COMPUTERIZED STATE-SPACE NETWORK ANALYSIS ALGORITHM

Christopher Pottle
Cornell University

Improvements and extensions to a previously reported technique have produced a versatile linear network analysis algorithm using the state-space approach. The speed and numerical accuracy of the resulting computer program offer advantages to industrial organizations, while research workers are finding it useful as a foundation upon which to build (e.g., an automatic design technique). The algorithms making up the complete analysis routine together with their mathematical foundations define a sizeable fortion of a modern course in circuit and system theory, to which the computer program is a useful adjunct. A review of a general method for obtaining state equations from network parameters is presented, followed by the description of an algorithm which produces without effort the state equations of the "inverse system", whose poles are the zeros of the original network. With this information in hand the QR algorithm can be employed to find poles and zeros of the network, since these are the eigenvalues of the A-matrices of the original and inverse systems, respectively. There follows a discussion of possible means for finding frequency and transient responses. The salient features of a computer program carrying out these operations is presented.

Session 1, Paper 1.7*

GINA-A COMPUTER GRAPHICS ANALYSIS SYSTEM

W. G. Magnuson, Jr.
Lawrence Radiation Laboratory

F. F. Kuo
University of Hawaii

W. J. Walsh
University of California, Berkeley

In this paper we give a brief description of a system for graphical I/O for circuit analysis and design. The system, called GINA (an acronym for Graphical Input for Network Analysis), is written in CALLIGRAPH, a low-level, FORTRAN-compatible language developed for the dd80 graphics display at Lawrence Radiation Laboratory, Livermore. We first examine the data structure and memory requirement of GINA. Next, we discuss the compatibility of GINA and many existing FORTRAN-based analysis programs such as CALAHAN, CIRCUS, and POTTLE. Finally, we compare GINA with other existing graphical I/O systems.

Work performed under the auspices of the U.S. Atomic Energy Commission.

Session 2, Paper 2.1

STATE-VARIABLE ANALYSIS OF RLC NETWORKS CONTAINING NONLINEAR COMPLING ELEMENTS

T. Ohtsuki and H. Watanabe
Nippon Electric Co., Japan

This paper deals with the state-variable analysis of the most general class of lumped time-invariant RLC networks.

The hybrid descriptions of coupled elements are discussed in connection with the mixed analysis of networks. Sufficient conditions for the uniqueness of solutions of coupled resistor networks and RLC netowrks are given in terms of hybrid descriptions.

The set of state variables are taken so that the order of state equations coincides with the number of finite natural frequencies in the linear case. A simple method for determining such a set of state variables by means of two particular trees, C-normal tree and L-normal tree, is also presented.

The standard form of state equations are represented by means of signal flow graph.

Session 2, Paper 2.2*

RECIPROCAL REALIZATION OF A-MATRICES

L. M. Silverman
University of Southern California

In this paper we consider the program of realizing a real n x n matrix as the A-matrix of a passive reciprocal network. That is, to find a network composed of passive resistors, transformers and n reactive elements for which the set of n first order differential equations

$$\dot{x} = Ax$$

describes the free behavior of n voltages and/or currents in the network. It is shown that a necessary and sufficient condition for such realizability is that A be a stable matrix (i.e., all of the eigenvalues of A are non-positive and those with zero real part have multiplicity one in the minimal polynomial of A).

Session 2, Paper 2.3

THE EXPLICIT FORM OF BASHKOW'S A-MATRIX FOR A CLASS OF LINEAR PASSIVE NETWORKS

J. Tow
Bell Telephone Laboratories

The explicit form of Bashkow's A-matrix for a class of linear passive nonreciprocal networks is derived. This result extends those already obtained for the reciprocal case as well as a special class of nonreciprocal networks. Necessary conditions for the passive networks to possess unique solutions, or equivalently, for the existence of the A-matrix, and the upper bound on the order of complexity are also discussed.

A proper tree in a resistor (R), capacitor (C) and gyrator (G) network N is defined as a tree of N in which both branches of each gyrator are either in the tree or in its cotree. The explicit form of the A-matrix is obtained for the class of RCG networks which possesses at least one proper tree and also satisfies a certain constraint involving the network topology and the non-reactive element values. The order of complexity for this class of networks is, in general, equal to the number of tree capacitors in any proper tree containing the largest number of capacitors.

Session 2, Paper 2.4

EXACT ANALYSIS OF LINEAR CIRCUITS CONTAINING A PERIODICALLY OPERATED SWITCH USING THE STATE SPACE APPROACH

M. L. Liou and F. R. Mastromonaco
Bell Telephone Laboratories

An exact analysis of linear lumped time-invariant circuits containing a periodically operated switch and a sinusoidal input using the state space approach is presented. Explicit, closed form solutions for both the time and frequency domains suitable for digital computation are obtained.

The analysis is applicable to any circuit configuration and can handle cases in which discontinuities in state variables occur at the switching instants. The method can also be extended to analyze linear circuits containing a single switch with more than two switchings in a switching period or multiple switches with a common switching period.

An immediate application of this analysis is the design of switched filters in time division multiplex systems.

Session 2, Paper 2.5

A UNIFIED MODELING SCHEME FOR SEMICONDUCTOR DEVICES WITH APPLICATIONS OF STATE VARIABLE ANALYSIS

T. Ohtsuki and K. Kani
Nippon Electric Co., Japan

A unified scheme for modeling semiconductor devices is presented. The main feature of this scheme is that it can be directly applied to state variable analysis. A distributed system, based on continuity, current flow relationship and Poisson's equations, is shown to be approximated by a lumped RC network in arbitrary accuracy. By means of this modeling scheme and state variable analysis technique, a network composed of semiconductor devices is formulated by a set of ordinary differential equations. The lumped RC network contains some C-only cutsets and circuits, which are corresponding to Poisson's equation and the conservative nature of the electrostatic field, respectively. Considering these topological structures, a set of state equations of minimum number of independent variables is systematically obtained.

An example of formulating a set of state equations of a 2-dimensional transistor model is given. Suggestions for applying the modeling scheme to various kinds of semiconductor devices are also given.

The modeling scheme proposed can be efficiently applied to the analysis of both a device itself and a network consisting of many devices over a wide range of conditions.

Session 2, Paper 2.6

RC SYNTHESIS OF THE A MATRIX

J. E. Steelman and S. Karni
University of New Mexico

A sufficient procedure is developed for the realization of Bashkow's A matrix based on an RC network with n degrees of freedom and (n+1) nodes.

The realization procedure generates C and Y (capacitance and conductance) matrices from the eigenvalues and eigenvectors of A, and then performs a congruent transformation using all possible tree submatrices. Linear programming is used to find the lengths of eigenvectors that lead to the hyperdominant C and Y matrices. With these and with the tree submatrix, an RC network and a tree can be realized.

Session 3, Paper 3.1

OPTIMAL LINEAR PROCESSING OF RANDOMLY DISTORTED SIGNALS

R. E. Maurer and L. E. Franks
Bell Telephone Laboratories

This paper considers least mean squared error linear estimation on signals received over a channel which can be characterized by additive noise sources and a time-invariant dispersion network whose transfer function is randomly selected. Solutions for the optimum linear receiver for the problem of continuous waveform estimation of a stationary process (Weiner filtering) and for estimating the amplitude of an isolated signal pulse (matched filtering) are presented and compared with the conventional results for a deterministic channel. The influence of the statistical properties of the channel dispersion on the optimal filter design is illustrated by examples involving particular models for the random channel. The investigation is extended to the situation where the receiver transfer function depends on a finite number of adjustable parameters, these parameters being set according to particular realizations of the channel characteristic. Conditions on the optimal form of this dependence are presented and typical results are illustrated by an example.

Session 3, Paper 3.2

A CLASS OF SIGNALS FOR TRANSMISSION IN THE PRESENCE OF INTERSYMBOL INTERFERENCE AND JITTER

P. E. Rubin* and L. Kurz
New York University

Properties of a class of signals with zero amplitude and zero derivative at all nonzero sampling points are investigated. Such signals are denoted as ZII-ZD (zero intersymbol interference-zero derivative) signals. ZII-ZD signals should prove useful in cases where timing jitter is significant.

Spectral requirements of ZII-ZD signals are obtained and it is shown that the unique minimum bandwidth member of this class is the $[(\sin\frac{\pi}{T}t)/\frac{\pi}{T}t]^2$ signal. Its bandwidth is twice the Nyquist bandwidth.

ZII-ZD signals with various useful properties are obtained. Minimum energy signals are derived and also signals whose frequency spectrum is zero over some interval.

An example is given of data system optimization under a mean-square error criterion when the received signal is constrained to be ZII-ZD.

Research in this paper was in part supported by the National Science Foundation under Grant GK-1075.
*On assignment from Bell Telephone Laboratories, Inc., Holmdel, New Jersey.

Session 3, Paper 3.3*

ON THE DESIGN OF RANDOM CIRCUITS

D. F. Elliott and D. D. Sworder
University of Southern California

Where applicable stochastic approximation provides a tool which permits the engineer to include component uncertainties in his design work. The question of convergence of this algorithm in circuit applications was explored by Gray using Dvoretzky's fundamental theorem. In this paper the problem posed by Gray is investigated and conditions sifficient to guarantee convergence are given a "sensitivity" interpretation. This interpretation is a natural one to circuit designers and also provides insight into ways that the method can be extended.

Session 3, Paper 3.4

APPLICATION OF VOLTERRA SERIES TO INTERMODULATION DISTORTION ANALYSIS OF TRANSISTOR FEEDBACK AMPLIFIERS

S. Narayanan
Bell Telephone Laboratories

This paper analyzes the intermodulation distortion of a solid state feedback amplifier. Each transistor of the amplifier has been represented by a frequency dependent model incorporating four nonlinearities. Volterra series is used as the analysis tool. The primary motivation for this study is that intermodulation distortion is a critical problem in high frequency, long haul, solid state systems.

A computer program, which calculates the amplifier intermodulation distortion, has been developed. This program can be used to select the optimum bias point of each stage, optimum interstage and feedback networks and optimum load and source impedances. Good correlation between calculated and measured result was obtained on a particular amplifier.

The closed form expressions derived show that the feedback is fully effective in reducing the open loop second order distortion, and, that the feedback may not reduce significantly the open loop third order distortion, if the 'second order interaction' phenomenon is dominant. The 'second order interaction' is explained in detail in the paper.

Session 3, Paper 3.5*

OSCILLATIONS IN BAND-PASS PHASE-LOCK LOOPS

G. Granello and F. Rocca
Istituto di Elettrotecnica e Elettronica, Italy

In this paper band-pass phase-lock loops are studied and it is shown that stability in the linear region of operation (small signals) does not guarantee the stability for higher values of the loop error. It is in particular shown that second order band-pass loops may be ustable and their limit cycles are given. Using then a method similar to the one of the describing function, general conditions for oscillation are given when a high-Q loop filter and a low frequency integrator are present in the loop.

Session 3, Paper 3.6*

MULTIMODE OSCILLATORS

Alwyn Scott
University of Wisconsin

Large one-dimensional (1D) and two-dimensional (2D) arrays of almost linear and almost lossless networks have been investigated to determine the possibility of multiple mode excitation. Quasiharmonic analysis indicates that serveral nonresonant modes should be stable on a 2D oscillator but unstable on a 1D oscillator. Experiments confirm that a variety of multimode oscillations, resonant as well as nonresonant, are observed on 2D oscillators but not on 1D oscillators.

Special Session 1, Paper S1.1

NONLINEAR RECIPROCAL NETWORKS

Robert K. Brayton
IBM Watson Research Center

There has been a growing tendency in writing the equations of electrical networks to keep the equations as simple as possible at the expense of having more equations. Some of the reasons for this will be explained. This leads to equations with canonical form

$$B\dot{x} = f(x,y,t) \tag{1}$$
$$0 = g(x,y,t)$$

rather than the standard normal form

$$\dot{z} = h(z,t) \tag{2}$$

It will be shown how the equations of the form (1) for nonlinear reciprocal electrical networks can be derived in the form

$$B\dot{x} = \frac{\partial P(x,y,t)}{\partial x}$$
$$0 = \frac{\partial P(x,y,t)}{\partial y}$$

The function $P(x,y,t)$ can be easily written down from the circuit diagram. Further, it will be shown how this function can be used to derive stability results by means of Liapunov function theory.

Special Session 1, Paper S1.2

ANALYSIS OF BISTABLE CIRCUITS

E. S. Kuh
University of California, Berkeley

A method has been developed to determine necessary and sufficient conditions for general resistive circuits to be potentially bistable. The method has been applied to well known bistable circuit configurations. The controlled-resistance model of transistors is used. The result of this study will lead to useful information for the optimum design of bistable circuits.

Special Session 1, Paper S1.3

ON THE SYNTHESIS OF TIME-VARIABLE PASSIVE CIRCUITS

R. W. Newcomb
Stanford University

Using the concept of nonnegative distributional kernels, properties required for the synthesis of finite passive linear time-variable circuits are reviewed.

By obtaining relationships between differential operators and their kernel representations, an operational calculus is set up for synthesis purposes. Through an extension of the non-commutative operator ring to its skew-field, the calculus is used to obtain a time-variable spectral factorization from which Bayard and Belevitch syntheses readily follow. Though the process is relatively general it does require difficult to calculate basis functions; consequently, alternate techniques are discussed and surveyed.

This research was supported by the Air Force Office of Scientific Research under Contract AFOSR F44620-67-C-0001.

Special Session 1, Paper S1.4

CIRCUIT THEORY AND OPTICS

A. Papoulis
Polytechnic Institute of Brooklyn

A system interpretation to small angle diffraction and thin lenses is developed. It is shown that the diffracted field on a plane parallel to the aperture can be considered as the output of a two-dimensional quadratic phase filter with input the incident wave. A lens is viewed as a pulse modulated linear FM multiplicative generator. The results are used to simplify the analysis of special filtering and diffraction limited image formation.

Analogies are established between optical and electrical systems. The analysis suggests novel solutions to a number of problems in signal theory. For example, it is shown that the pulse compression technique used in radar is the direct analog of the old principle of the concentration of light by a lens.

The analysis is extended to random waves. The coherence properties of the diffracted field of the image of an incoherent object are determined from the relationship between the input and output autocorrelations of a linear system. Special cases are discussed.

Special Session 1, Paper S1.5

COMPUTER AIDED ANALYSIS OF NONLINEAR CIRCUITS

T. E. Stern
Columbia University

In principle, the time domain analysis of nonlinear networks is simply a matter of solving the set of nonlinear differential equations, presumably a routine task for a digital computer. There are, however, certain characteristics of these networks which pose special difficulties not normally encountered in other areas of applications. This paper discusses certain common problems that arise, together with a numerical technique that shows some promise in circumventing these problems.

The related question of determinacy constraints and large ratio of time constants is first considered. Then a brief critique of existing computer-based methods of time domain analysis is followed by an exposition of a novel numerical approach based on a computerization of limiting solution of a set of network equations containing small parameters. Computation results comparing this method with more conventional approaches are presented and analyzed.

Session 4, Paper 4.1

THE SYNTHESIS OF MICROSTRIP TRANSMISSION NETWORKS UTILIZING SEMICONDUCTOR DIELECTRICS

A. W. Cuilwik
Bell Telephone Laboratories

J. H. Mulligan, Jr.
New York University

A class of filter networks is investigated which consists of sections of microstrip transmission lines employing a semiconductor dielectric operating between resistive terminations. The result obtained by Richards for networks consisting of resistors and lossless transmission line sections is generalized to treat the transfer function of a two-port composed of a lossy distributed network with resistive terminations. It is shown how the transfer functions of this class of lossy networks can be expressed in the same form as corresponding functions for lossless structures, thus making feasible the application of synthesis methods already available for lossless structures.

A design procedure is presented for the systematic synthesis of this class of networks. The procedure is illustrated by several design examples including both maximally-flat-magnitude and Chebyshev bandpass filters.

Two filters were fabricated using micrestrip sections containing a high-loss silicon dielectric. The measured and calculated responses of both filters were in good agreement.

Session 4, Paper 4.2

ACTIVE NETWORK SYNTHESIS USING AMPLIFIERS HAVING ANY FINITE NONZERO GAIN

D. Hilberman
Bell Telephone Laboratories

A synthesis method is presented which uses a current-controlled current source and a capacitor to form an integrator. This integrator is used in conuunction with voltage-controlled voltage sources and resistors to form a current transfer network whose block diagram closely resembles standard analog computer circuits. The surprising feature of this approach is that the amplifier gain can have any finite nonzero value and therefore, it it is desirable, one can use amplifiers with less than unity gain.

The synthesis method realizes current transfer functions directly. With minor additions voltage transfer networks and driving-point admittance networks can be realized. These methods are extended to (N+1) - terminal common-ground networks to realize various network matrices.

Session 4, Paper 4.3*

SYNTHESIS OF NIC AND NEGATIVE-RESISTANCE NETWORKS

Chang-Kiang Kuo and Kendall L. Su
Georgia Institute of Technology

In this paper an analytical and systematic procedure is developed to realize NIC and -R (or bistable) circuits using two bipolar and/or field-effect transistors. Basic nonideal NIC circuits are first synthesized by performing interconnections of two elementary networks, each of which contains one transistor. Useful elementary networks are given with their respective mathematical matrices. All basic nonideal NICs are identified by checking their matrix parameters to satisfy the criteria for a nonideal NIC. Practical operational NICs are then implemented by carrying out the dc biasing and the compensation of parasitic parameters. Two -R (or bistable) circuits are derived from each nonideal NIC by terminating it in a resistor at either port. Each NIC renders two -Rs -- one is current-controlled and one voltage-controlled. An example is given for the development of an ac and a dc model NICs from a basic nonideal NIC circuit using two FETs. Many -R circuits are shown in their final operational forms.

Session 4, Paper 4.5

THE ACTIVE RC LINE--A FAMILY OF NEGATIVE-CONDUCTANCE CIRCUITS

T. P. Kabaservice
Virginia Polytechnic Insitute

A small-signal analysis of a type of active transmission line is presented. This line is in the form of a ladder network having positive resistance in the series branches and voltage-stable negative-conductance devices in the shunt branches. The product of total series resistance (R) and total shunt conductance (G) is shown to be a parameter that describes the transfer properties of lines containing any number of identical sections. A simple stability criterion is presented, and some aspects of input matching and available power gain are discussed. Experimental models have been constructed, whose characteristics support the principal predictions of theory.

Session 4, Paper 4.7*

A SECOND GENERATION CURRENT-CONVEYER AND ITS APPLICATION

A. Sedra and K. C. Smith
University of Toronto, Canada

The present paper introduces a new versatile building block with powerful termina-characteristics employing the current conveying principle. This new block, termed CC II, is a tree port network characterized by

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}$$

The paper demonstrates the application of these terminal characteristics to the implementation of the four types of controlled source, and hence to the broad area of active network synthesis. Shown for example are simple direct implementations of NIC and NIV devices with dc coupling and large signal operations.

CC II can also be used as a general purpose analog computation element. Three circuit implementations for the CC II are described. A large signal analysis and design of one of them incorporating a nearly ideal buffer stage is carried out in detail.

Session 5, Paper 5.1

MULTI-LAYER DISTRIBUTED NETWORKS

F. Y. Chang and O. Wing
Columbia University

A multi-layer RC distributed network is formed when layers of dielectric and resistive materials of uniform width and thickness are alternately sandwiched. The immittance functions of such a network admit canonical forms which lead to equivalent networks consisting of decoupled uniform RC lines. The voltage transfer function is found to have a low-pass, band-pass or high-pass characteristic with an absolute value possibly greater than unity over a range of frequencies. Necessary and sufficient conditions are given for a transcendental frequency function to be a network function of a multi-layer RC distributed network. The realization procedure is derived and illustrated by numerical examples.

Session 5, Paper 5.2

CASCADE SYNTHESIS OF DISTRIBUTED RC NETWORKS

J. O. Scanlan and N. Ramamurty
University of Leeds, Great Britain

The synthesis of simultaneously prescribed driving point and transfer admittances for distributed RC networks without transformers is considered. Realizations with common ground connections are required. The realizations given, in general, involve an arbitrary multiplying constant for the transfer admittance and are valid except when the prescribed transmission zeros, $t = \tanh \sqrt{p} = \sigma_0 + j\omega_0$ are such that $\omega_0^2 < \sigma_0^2 < 1+\omega_0^2$. If only the short-circuit transfer admittance, y_{12}, or the open-circuit voltage transfer ratio, T_{12}, is specified a realization using surplus factors is given valid for all transmission zeros other than real zeros less than unity, which can never be realized by an unbalanced commensurate distributed RC network, and that for such networks zeros of transmission where $\sigma_0^2 > \omega_0^2 + (\sigma_0^2+\omega_0^2)^2$ always require the use of surplus factors. Examples of the various synthesis procedures are given.

Session 5, Paper 5.3*

A NEW CLASS OF NON-UNIFORM DISTRIBUTED RC FILTERS

Tsai-hwa Chen
University of California, Los Angeles

By reducing the RC-transmission line equation to the Cauchy's linear differential equation, a complete new class of non-uniform distributed RC line is found. This new class of line is named as $\overline{\text{CRC}}$ which stands for the distributed RC line governed by the Cauchy's equation. In comparison with presently existing RC lines, the $\overline{\text{CRC}}$ has some freedom in fabrication but offers the same performance as that of the exponentially tapered RC lines, $\overline{\text{ERC}}$.

The equivalent conditions between $\overline{\text{CRC}}$ and $\overline{\text{ERC}}$ are found. The network functions of $\overline{\text{CRC}}$ are derived and co-relations among the two-port transfer functions may be expressed in terms of a single low-pass transfer function G_{vl}. Different orders of approximation for G_{vl} are developed with different accuracy for various engineering applications. Trade-off between the accuracy and calculation complexity can be made in engineering design and the synthesis of $\overline{\text{CRC}}$ is possible by using these approximation equations. Transient response are studied by the residue method and the Ekmore's method. Their results are compared with the exact solution and the experimental observations. The experimental results on the frequency response of $\overline{\text{CRC}}$ and $\overline{\text{ERC}}$ are presented to indicate the good agreement with the theoretical predictions. Computer plotted curves are also included in Appendix to show the accuracy of various orders of approximation.

Session 5, Paper 5.4

ANALYSIS OF RECTANGULAR RC DISTRIBUTED CIRCUITS WITH SHAPED ELECTRODES

K. W. Heizer
Southern Methodist University

An analysis is given for a distributed RC network which consists of a resistive layer separated by an insulator from three separate electrodes. A conducting tab is placed completely across two opposing ends of the resistive layer. These tabs form two terminals of a five-terminal network. The three electrodes form the other terminals. The short circuit admittance parameters for this network are derived and consideration is given to special interconnections. The short circuit transfer admittances between an electrode and either end of the resistive layer may easily be made rational. An interconnection provides the possibility of a rational short circuit transfer admittance which does not possess a zero at the origin. The method can be extended to similar multi-electrode networks.

Session 5, Paper 5.6

SYNTHESIS OF NONUNIFORM RC DISTRIBUTED CIRCUITS

E. D. Walsh and C. M. Close
Rensselaer Polytechnic Institute

A synthesis procedure by which any RC-realizable, rational transfer function can be realized as the open-circuit voltage transfer ratio of a nonuniform RC distributed circuit is presented. The synthesized circuits all have a standardized topology, with only the nonuniform tapers of the circuits depending on the specified transfer function. An iterative scheme, similar to those found in optimal control systems, is used to compute a resistance taper that realizes the desired poles. Then the capacitance taper is determined so that the transfer function has the specified zeros and is rational in the complex frequency variable s. Finally, modifications are made to facilitate construction of the circuit, without changing the transfer function.

The circuits have resistive and dielectric layers of uniform thickness and composed of homogeneous material. Therefore, they can be readily constructed using present-day thin film techniques. The synthesis procedure has been completely programmed on a digital computer. From the basic data specifying the transfer function and the electrical properties of the construction materials, the computer determines all the geometrical dimensions necessary for the construction of the circuit. Experimental measurements on models made from resistive and dielectric paper are in good agreement with the theoretical results.

session 5, Paper 5.7

SYNTHESIS OF TAPERED DISTRIBUTED RCG NETWORKS

Samuel C. Lee
New York University

The synthesis of a broad class of tpaered distributed RCG ($\overline{RCG}$) networks which include uniform ($\overline{URCG}$), exponential ($\overline{ERCG}$), hyperbolic cosine-squared ($\overline{HCRCG}$) hyperbolic sine-squared ($\overline{HSRCG}$), trigonometric ($\overline{TRCG}$), and square ($\overline{SRCG}$) tapered networks, is investigated. The necessary and sufficient realizability conditions are presented. It is shown that by using some suitable transformations, this class of networks may be obtained from any of the known lumped passive or active RC synthesis methods. A complete synthesis procedure is given. Relations among sensitivity functions of this class of networks are presented. The stability conditions of this class of networks are also given.

Special Session 2

PANEL DISCUSSION ON COMPUTER AIDED NETWORK DESIGN

Chairman: D. A. Calahan, University of Michigan

Circuit Analysis and Optimization:

Moderator: F. H. Branin, Jr., IBM

Panel: L. O. Chua, Purdue University

M. L. Dertouzos, MIT

P. E. Fleischer, Bell Telephone Laboratories

Modeling:

Moderator: G. D. Hachtel, IBM

Panel: F. A. Lindholm, University of Florida

R. D. Thornton, MIT

H. Schichman, Bell Telephone Laboratories

Session 6, Paper 6.1

DISTINGUISHABILITY CRITERIA IN DIRECTED GRAPHS AND ITS APPLICATION TO COMPUTER DIAGNOSIS

W. Mayeda and C. V. Ramamoorthy
University of Texas

Discrete sequential systems like the functional elements of a digital computer can be represented by directed graphs. In this paper we study an application of graph theory to computer diagnosis. Specifically, we develop the distinguishability criteria in directed graphs and derive bounds on the number of test points needed to locate faults in a sequential system.

Session 6, Paper 6.2*

TOPOLOGICAL ANALYSIS OF NETWORKS CONTAINING NULLATORS AND NORATORS

G. S. Brayshaw
The City University, London

Rules are given which enable a simple graphical method to be used for obtaining the determinant Δ and its cofactors Δ_{ij} corresponding to the nodal admittance matrix of a linear network containing nullators and norators.

Session 6, Paper 6.3

ON THE DECOMPOSITION OF NETWORKS IN MINIMALLY INTERCONNECTED SUBNETWORKS

F. Luccio and M. Sami
Politecnico of Milano, Italy

The problem is discussed of decomposing a network in different groups of electrical components, which are interconnected by the minimum number of leads. Minimal groups of components are defined as subnetworks, fulfilling a chosen minimality criterion; the set of all such groups constitutes the proposed decomposition for the network.

A number of properties is presented and proved for minimal groups. First property, showing the structure of the decomposition, is that minimal groups can totally but not partially overlap. Other properties are useful for the determination of minimal groups. In fact, an ordered procedure based on these properties is illustrated, to determine all the minimal groups in a given network. The procedure has been developed for direct computer implementation.

CONNECTIVITY CONSIDERATIONS IN THE DESIGN OF SURVIVABLE COMMUNICATION NETWORKS

H. Frank and W. Chou
Office of Emergency Planning
and University of California, Berkeley

The problem of construction networks which are "survivable" with respect to branch damage is considered. The networks are modelled by linear graphs and a square symmetric "redundancy" matrix $R' = [r'_{ij}]$ is specified. Algorithms are given to construct an undirected graph G with a minimum number of branches such that

(a) G contains no parallel branches

(b) For all i,j there are at least r'_{ij} branch disjoint paths between the i-th and j-th vertices.

These algorithms are complicated but may easily be applied to construct graphs with several hundred vertices.

THE DESIGN OF MINIMUM-COST SURVIVABLE NETWORKS

K. Steiglitz
Princeton University

P. Weiner
Princeton University

D. J. Kleitman
Massachusetts Institute of Technology

We consider the problem of designing a network which satisfies a prespecified survivability criterion with minimum cost. The survivability criterion demands that there be at least r_{ij} node disjoint paths between nodes i and j, where (r_{ij}) is a given redundancy requirement matrix. This design problem appears to be at least as difficult as the traveling salesman problem, and present techniques cannot provide an exact solution that is computationally feasible.

A heuristic approach is described, based on recent work on the traveling salesman problem, which leads to a practical design method. Algorithms are described for generating starting networks, for producing local improvements in given networks, and for testing the redundancy of networks at each stage. This leads to networks which are locally optimum with respect to the given transformation. Randomizing the starting solution ensures that the solution space is widely sampled. Two theorems are given which allow great reduction in the amount of computation required to test the redundancy of a network. Finally, some design examples are given.

Session 6, Paper 6.6*

NECESSARY AND SUFFICIENT CONDITIONS FOR REALIZABILITY OF VERTEX-WEIGHTED COMMUNICATION NETS

I. T. Frisch and N. P. Shein
University of California, Berkeley

A counter example is given to show that the necessary and sufficient conditions for realizability of a matrix as the terminal capacity matrix of a vertex weighted communication net, which were given in 1962, are only necessary but not sufficient.

A new set of necessary and sufficient conditions are proposed and proved. In the process of developing these conditions new properties and refinements in the description of a terminal capacity matrix are developed; a new realization algorithm is introduced which depends crucially on the correct necessary and sufficient conditions; finally the realizability conditions for special classes of graphs, such as trees, are obtained as immediate consequences of the complete set of necessary and sufficient conditions.

Research sponsored by the Joint Services Electronics Program under Grant AF-AFOSR-139-67 and AFOSR-68-1488 and the U. S. Army Research Office--Durham under Contract DAHCO-67-0046.

Session 6, Paper 6.7*

SYNTHESIS OF RELIABLE NETWORKS

J. D. Leggett and S. D. Bedrosian
University of Pennsylvania

Probabilistic networks have been receiving increasing attention in the literature. In this paper graph theoretic methods are applied to a restricted class of networks. The branches are assumed to be equiprobable and uncorrelated. Further, the branch capacities are assumed adequate. The criterion of invulnerability is that the graph remain in one connected piece. The most reliable network is characterized by the possession of the maximum number of trees. Tight closed form bounds on the reliability are obtained. Synthesis problems, wherein a minimum reliability is prescribed, using branches of given reliability, are solved.

Session 7, Paper 7.1

A CLASS OF TIME-VARYING DIGITAL FILTERS

B. Liu
Princeton University

P. A. Franaszek
IBM Research Laboratory

Discrete-time signals and digital filters have become increasingly important in recent years with the rapid advance of technology in integrated digital circuitry and the increasing availability of digital computers. This paper is concerned with a class of linear time-varying digital filters and the response of such filters with stochastic input signal. It is shown that these filters possess a number of useful properties; the most important of which is the preservation of wide sense stationarity of stochastic inputs. Such properties can facilitiate considerably the analysis of systems incorporating these filters. It is shown that this class is the most general class of time-varying filters which preserve the wide sense stationarity of the inputs. A subclass of these filters is shown to be periodic and hence can be implemented simply by using parallel connection of time-invariant filters and a rotating switch. The response of these filters to periodic inputs is analyzed.

The research at Princeton is supported by the National Science Foundation under Grant GK-1439.

Session 7, Paper 7.2

A GENERAL THEORY OF COMMUTATED NETWORKS

Y. Sun*
University of Wisconsin

I. T. Frisch
University of California, Berkeley

A general state space approach is used to deriva an exact closed form solution for both the transient and steady state response of a multiport commutated network. By expanding the time varying transfer function in a Fourier series the transfer function at input and harmonic frequencies is then calculated. From the general analysis we immediately obtain previously available results on comb filters, n-path filters, sampled data filters and digital filters.

Since the results are closed form solutions in terms of element values, they are most suitable for computer simulation in which the performance of the commutated network is to be evaluated as the element values are varied.

*Formerly with University of California, Berkeley.

The research reported herein was sponsored by the Joint Services Electronics Program under Grant AF-AFOSR-139-67.

Session 7, Paper 7.3*

NONLINEAR ANALYSIS OF PARAMETRIC AMPLIFIERS

M. Goldstein and H. Frank
University of California, Berkeley

The parametric amplifier has stimulated considerable interest in the past decade as a method of low noise amplification in the microwave frequency range. It has usually been analyzed by replacing the nonlinear element by a time varying linear one and analyzing the resulting network.

This paper begins with a nonlinear model for a parametric amplifier which may be approximately described by a set of nonlinear algebraic equations. From these equations gain and bandwidth are calculated, saturation effects are predicted, and a small signal gain formula is derived. The exact solution to the equations is discussed, and its relation to the small signal solution and to the linear time varying approximation is noted.

To test the validity of this approximate analysis, the differential equations for the circuit were integrated on a digital computer. The results obtained also give information useful in designing filters for the device, in studying harmonic distortion, and in verifying the small signal gain formulas derived by various methods.

Session 7, Paper 7.4*

THEORY OF QUASI-SINUSOIDAL NON-LINEAR NETWORKS

T. Suezaki and S. Mori
Keio University, Japan

This paper presents some general theory of non-linear network for almost sinusoidal steady states. In particular, emphasis is placed on the stability criterion for periodic steady states. An equivalent linearization method based on vector power relations in non-linear elements and some remarks for construction of network equations are introduced. The concept of the stability criterion is founded on complex frequencies which describe behaviors of amplitude and phase motion in the vicinity of periodic steady states, and some examples are shown. The main advantages of this method are that it is easily used and understood, and formally applicable to any order systems.

Session 7, Paper 7.5*

SENSITIVITY ANALYSIS AND MODELS OF NON-LINEAR CIRCUITS

Sydney R. Parker
U.S. Naval Postgraduate School

Sensitivity functions for a non-linear circuit may be obtained by calculating the corresponding responses of a circuit topologically identical to the original in which each component is replaced by its dynamic linear equivalent evaluated at the operating current or voltage. The source function for the sensitivity model depends upon the sensitivity parameter and is a voltage source in series with the component for resistance and inductance elements; and a current source in parallel with the component for capacitance and conductance elements. The source is always directed to oppose the direction of current flow through the component in the roiginal circuit. The value of the source is determined by the slope of the functional relationship between the voltage and current with respect to the sensitivity parameter for resistive elements, and the time rate of change of the slope of the functional relationship between charge versus voltage, or flux versus current, with respect to the sensitivity parameter for energy storing elements. The results are shown to lend themselves to the same type of computer programming as used to solve the original circuit.

Session 7, Paper 7.6

SOME SYNTHESIS METHODS FOR ADJUSTABLE NETWORKS USING MULTI-VARIABLE TECHNIQUES

James F. Delansky
Pennsylvania State University

The synthesis of the class of adjustable networks which respond or adapt to an independent (with respect to frequency) real variable, or several such independent real variables, and which for fixed values of these variables respond as linear time-invariant networks, is considered. For this class, the network functions (possibly after some frequency transformations) are real and rational in (possibly) several frequency variables, and the coefficients of the numerator and denominator polynomials in the several frequency variables are real functions of the real independent variables.

Most synthesis procedures for adjustable networks use adjustable elemtns that are assumed to be highly versatile in their functional form. Practically, however, such adjustable elements may not exist. Also, a serious tracking problem results when more than one type of adjustable element for each independent real variable is used.

The synthesis methods developed here allow the designer 1) to choose a single type of adjustable building block for each independent real variable, 2) to maintain control of the functional complexity of these adjustable blocks, and 3) to use, in the single real variable case, only the absolute minimum number of such adjustable blocks.

Session 8, Paper 8.1

GAIN BANDWIDTH PROPERTIES OF A DISTRIBUTED PARAMETER LOAD

Herbert J. Carlin and Robert A Friedenson
Cornell University

The gain bandwidth restrictions are considered for a distributed parameter load consisting of a resistor shunted by an open-circuited stub of delay length τ. An aperiodic solution for the optimum flat gain response in the frequency domain is obtained by using a computer solution which solves the infinite set of simultaneous constraint equations associated with the infinite number of periodically spaced load transmission zeros. It is shown that this solution converges to the largest gain-bandwidth product when only the fundamental frequency band is permitted and all higher order periodicities of the frequency response are properly suppressed by progressively shifting the center frequency of the higher order pass bands, as their gains are attenuated. Furthermore, a new result for optimum flat gain periodic response is obtained. In this case the equalizer is a cascade of commensurate lines each of length $\tau/2$. This gives twice the gain of the best periodic equalizer employing lines equal to the stub length τ. Finally, synthesis techniques for realizing the periodic equalizer are discussed.

This work was supported under NSF Grant GK-2147, and by means of an NSF Traineeship.

session 8, Paper 8.2

FOSTER DISTRIBUTED-LUMPED NETWORK SYNTHESIS

G. T. Daryanani and J. A. Resh
Michigan State University

Sufficient conditions are developed for the realizability of frequency-domain, non-rational, immittance functions. The networks consist of distributed and lumped elements (RC and RL) and have Foster-type topologies.

The approach used is to classify functions by their singularities. The functions may have a discontinuity across a line on the negative real axis of the s-plane. This class includes p.r. branches of multivalued functions with branch points as their singularities. The theory utilizes properties of integrals with a Cauchy-type kernel evaluated along the line of discontinuity. Such integrals have been discussed by Muskelishvili in his work on singular integral equations.

The functions could also have a countably infinite number of poles on the negative real axis. Mittag-Leffler's theorem gives representations for such functions which yield Foster-type infinite-lumped networks.

An open question is--can p.r. immittance functions which are RC, RL realizable have any other singularities?

Session 8, Paper 8.3*

THE DRIVING POINT SYNTHESIS OF FINITE LOSSLESS NONUNIFORM LINES TERMINATED IN A RESISTIVE LOAD

Emmanuel N. Protonotarios and Omar Wing
Columbia University

A finite lossless nonuniform transmission line, which may contain discontinuities and lumped elements, is considered. The line is characterized by the function $C=\sigma(L)$, $L\varepsilon(0,L_T)$ with $CT=\sigma(L_T)$, $(L_T<\infty, C_T<\infty)$, where L and C are the cumulative inductance and cumulative capacitance respectively, and L_T, C_T are the corresponding total inductance and capacitance. The function $\sigma(L)$, $L\varepsilon(0,L_T)$ is nondecreasing and otherwise arbitrary.

A set of necessary and sufficient conditions that a function Z(s) is the input impedance of such a line terminated in a resistive load (not necessarily matched) is given. These conditions are presented as alternatives to existing results on lines with a local characteristic impedance which is twice or infinitely differentiable or absolutely continuous with a matched load, when no continuity conditions or matched terminations are considered. We thus attempt to find the most general class of impedance functions Z(s) realizable by resistively terminated finite lossless lines.

We also propose a "Caurer" like approximate synthesis procedure for such lines.

This work was supported by the National Science Foundation under NSF Grant GK-2228.

Session 8, Paper 8.4

THEORY AND DESIGN OF COMMENSURATE TRANSMISSION LINE ALL-PASS NETWORKS

Edward G. Cristal
Stanford Research Institute

A general theory of commensurate transmission line all-pass equalizers operating in either TEM, TE, or TM modes is presented. It is shown that the equalizer network consisting of a three-port circulator having (1) the second port terminated in a reactance network of cascaded commensurate transmission lines, and (2) a matched line $n\theta$ long in series with either the input or output port is a canonical network capable of realizing any allowable all-pass commensurate transmission line network transfer function. The network of cascaded commensurate transmission lines is intimately related to the Hurwitz polynomial of the transfer function, and a recursion formula for this relationship is established.

Although the theory, strictly speaking, is for commensurate transmission line networks, it is not essential that the network being equalized, or even the equalizer itself, be of commensurate length lines. Formulas for narrow-band equalizers of up to two cavities are presented, and a method of extending the design to a greater number of cavities is described.

Session 8, Paper 8.5*

THE SYNTHESIS OF UNIFORM DISTRIBUTED RC NETWORKS WITH LUMPED TERMINATIONS

Jack Stein, J. H. Mulligan, Jr., and S. S. Shamis
New York University

This paper considers the synthesis of uniform RC distributed networks terminated in prescribed lumped RC load impedances by utilizing functions of the hyperbolic tangent to represent driving point impedance functions of open-circuited and short-circuited RC transmission lines as approximating functions for the lumped loads. The approximation of the lumped impedance takes two forms. The first employs simple functions of the hyperbolic tangent with an RC product which is a fraction of that of the line sections, whereas the second uses rational functions of the hyperbolic functions with an RC product equal to that of the line sections. It is shown how the error introduced by the approximation can be controlled in the design process. Examples are given of the use of the approximation methods in the adaptation of the Bower-Ordung lumped synthesis procedure to distributed RC networks; and finally, the results obtained by the two methods are compared.

session 8, Paper 8.6*

TRIPLE DISTRIBUTED NOTCH FILTERS AND SOME ACTIVE FILTER APPLICATIONS

R. E. Parkin
Bell Telephone Laboratories

Following an analysis of the triple uniformly distributed RC network, the solutions for real frequency zeros of three types of connection are presented. Typical frequency responses are given. It is shown that the filters can approximate more closely an ideal low-pass filter by loading the networks with a negative resistor and negative capacitor in parallel. With this type of loading a complex pole pair is available to be placed anywhere in the complex frequency plane; choosing the pole pair to be close to the real frequency axis, at a lower frequency than the real frequency zeros, produces a response of 30 db/octave or greater at the 3 db frequency.

Session 8, Paper 8.7*

ACCURATE TRANSFER MATRIX CALCULATIONS FOR ARBITRARILY TAPERED MULTILAYERED DISTRIBUTED NETWORKS

Edward C. Bertnolli and Robert C. Peirson
University of Missouri, Rolla

This paper presents a numerical method for calculating the transfer matrix of a multilayered distributed parameter network having an arbitrary taper. After division of the network into n sections, the transfer matrix of each section is approximated using the first r terms of the matrices' Taylor's series. The accuracy of this method depends on n, the number of sections, and r, the order of the Taylor's series approximation. An expression for the normed solution error is developed which displays the relationship between the error and the approximation parameters r and n. This expression provides a bound on the solution error that aids the analyst in selecting his solution accuracy prior to calculation of the transfer matrix. An example is included to illustrate the application and speed of this method.

This method, although cast in terms of distributed network theory, may be applied to the analysis of linear time varying systems.

Session 8, Paper 8.8*

SYNTHESIS OF STABLE NETWORK FUNCTIONS USING DISTRIBUTED RC-STRUCTURES

J. C. Giguere, M. N. S. Swamy, and B. B. Bhattacharyya
Nova Scotia Technical College, Canada

This paper deals with both the passive and active synthesis of network functions using nonuniform RC-lines. The passive synthesis part is mainly concerned with the synthesis of transfer functions using symmetric RC-lines. Necessary and sufficient conditions are presented for the synthesis of transfer functions using a structure, which is a cascade of two networks N_1 and N_2, N_1 being a ladder network whose different elements are cascades of symmetric lines and N_2 being a cascade of n symmetric lines. An extension considers a parallel interconnection of such structures.

On active synthesis, a sufficient condition is established for the stability of a network function that may be realized by a network consisting of active elements and an interconnection of impedances proportional to p(s) and q(s), these being either any two one port impedances of a given RC-line or the impedances of any two lines. The actual realization of the network function may be carried out using any of the known procedures of lumped RC-active synthesis. The realization of stable transfer and driving point functions is considered in some detail.

COMPUTER AIDED ANALYSIS FOR INTEGRATED CIRCUITS

Jan A. Narud
Motorola

Michael L. Dertouzos
Massachusetts Institute of Technology

G. Peter Jessel

With the advent of integrated circuits the requirement for accurate prediction of circuit performance has become exceedingly important because of the cost involved in making integrated prototypes and because the models of the elements constituting the integrated circuits are more complex in nature than in the discrete counterpart of the circuit. Also, the demand for a great variety of different circuits as well as the requirement for a quick turn around time makes the need for short design cycle time imperative. Moreover, with the emergence of more complex arrays, testing and diagnostic procedures become an intimate part of the design. Since there is a limited amount of design engineering effort available and also a finite amount of time that can be spent on a particular design, computer aided design has become an absolute necessity in order ot economically arrive at a good engineering compromise.

In this paper the marriage between integrated circuit design and design automation will be explored. First a brief review of the typical processes and design requirements (such as limiting factors, lay out rules, etc.) for integrated circuits will be discussed with particular attention to the following analysis needs:

I. D.C.Analysis
   A. Typical performance characteristics
   B. Worst case analysis
   C. Statistical analysis (Monte Carlo method)
   D. Worst case statistical analysis
II. Transient and/or frequency performance
III. Power and heat dissipation
IV. Reliability
V. Computer aided mask generation
VI. Ohmic drops and power supply tolerances
VII. Test and diagnostic algorithms

Then a brief review of the capabilities and limitations of state of the art computer aided design will be given. Here, batch, remote batch and interactive multiplex time sharing systems will be briefly reviewed. Particular attention will be given to machine limitations, such as sotrage requirements, number of iterations required for typical programming routines, design time, etc., and how these limit the analysis of the practical size of the complexity of integrated circuits. These limitations usually take the form of the number of elements, nodes, branches, the

complexity of the model for the element to be nested in the circuit analysis problem. From the result of this discussion it will be fairly evident that analysis of a typical complex integrated circuit will exhaust the capacity of even the largest machines today, and if not the analysis routine will take too long to be economically feasible to prepare. The solution to this problem is to "microanalyze" the integrated circuits up to the gate or flip-flop level and from these results develop a simplified macro model for these circuits. Complex arrays or the application of integrated circuits in systems are then analyzed using the macro model as the basic building block. In the paper it will also be demonstrated how optimization and interactive design can be accomplished utilizing the macro approach.

Finally the paper will consist of some descriptive examples illustrating points such as nesting of macros, optimization of the power speed products of gate, and the mask generation of integrated circuits.

Session 9, Paper 9.2

COMPUTER DESIGN OF TEMPERATURE DESENSITIZED INTEGRATED SELECTIVE AMPLIFIERS

W. G. Howard and W. J. Walsh
University of California, Berkeley

A computerized design procedure for integrated selective amplifiers which is capable of desensitizing network functions to both linear and nonlinear component temperature variations is presented. The underlying theoretical basis for the procedure is related directly to classical pole sensitivity and serves as the basis for establishing minimum complexity of a desensitized circuit. The network to be sensitized can be described either topologically or as poles and zeros of an open-loop transfer function. The variable elements are assigned linear and second order temperature coefficients. This information serves as input to an optimization procedure which searches for the sensitivity minimum.

The final solution is statistically analyzed for variations in performance due to tolerance of element values. This statistical analysis can be used to predict yield figures.

Research sponsored by the Joint Services Electronics Program under Grant AFOSR-68-1488.

Session 9, Paper 9.3

THE DESIGN OF HYBRID INTEGRATED FILTER BUILDING BLOCKS

G. S. Moschytz and W. Thelen
Bell Telephone Laboratories

An economical approach to integrated active RC filter design is described. Complex filter networks are broken down into a small family of cascadable second-order filter building blocks consisting of tantalum thin-film RC networks and semiconductor integrated operational amplifiers. The same building blocks are used for any desired filter configuration such as low-, high-, or bandpass filters, all-pass networks, notch filters, etc.

The paper first describes a synthesis method lending itself particularly well to the building block design of active filters. This design approach, combined with the characteristics of tantalum and silicon integrated circuits is ideally suited for high Q networks with excellent stability. The basic network configurations are derived and the topologies presented that provide any desired linear bumped-parameter finite network. The operational amplifier characteristics required for the building blocks are specified, as are those of the thin-film RC components. A detailed design example of a pulse shaping network consisting of both minimum and nonminimum phase networks is given.

Session 9, Paper 9.4

COMPUTER AIDED CIRCUIT DESIGN BY CONSTRAINED SINGULAR IMBEDDING

M. A. Murray-Lasso and E. B. Kozemchak
Bell Telephone Laboratories

Computer aided circuit design has had its greatest impact in the area of analysis. Network theory has been of limited utility in the synthesis of electronic networks by computer. In this paper the scope of circuit theory is generalized to include two classes of elements useful in electronic network design. The first class, which generalizes the allow pairs of a nullator, is used to constrain network variables. The second class, which limits the allowed pairs of the norator, is used to represent bounded adjustable elements. Both classes allow relations as well as function in their definition. By imbedding these elements into a network, the synthesis problem can be transformed into a problem of analysis of a circuit containing singular elements. The formulation remains linear throughout.

Computer programs for time-share use have been written to provide a direct on-line design system that avoids the usual iterative optimization-analysis approach. Several examples are presented, one illustrating the design of a transistor amplifier, the other illustrating the bias of a differential amplifier.

Session 9, Paper 9.5

COMPUTER-AIDED DESIGN OF DISTRIBUTED RC NETWORKS

Samuel C. Lee and Suleyman S. Penbeci
New York University

In this paper synthesis of distributed RC networks using nonlinear programming is investigated. The Fletcher-Powell minimization procedure is used to minimize the integral squared error. At the same time, the decreasing of the error in the Chebyshev sense is examined in each iterative cycle. One of the main considerations in applying nonlinear programming to a design problem is to find an initial design such that by iterating which in the frequency range of interest, not only the iteration is guaranteed to converge to a minimum within a reasonably short computing time, but also the minimum obtained possibly is a global minimum. Two methods for finding such an initial design are presented. One is making an approximation of the given network function in the complex frequency plane and the other is making an approximation of the given network function in a transformed complex frequency domain. Both approximations are obtained by means of orthogonal functions. The methods presented in this paper may be used for practical distributed RC network applications. Examples are given to illustrate the methods.

Session 9, Paper 9.7*

ON THE SELECTION OF ISOLATED REGIONS IN COMPUTER-AIDED DESIGN OF INTEGRATED CIRCUITS

Domenico Ferrari
Politecnico di Milano, Italy

One of the inital steps in the design of bipolar integrated circuits is the partition of circuit components into classes which must be fabricated in electrically isolated regions. In this paper, the problem is discussed of selecting this partition with the aid of a computer. An algorithm is described which determines the minimum number of isolated regions and the components that can be included in each region. A systematic, easily programmable method is also proposed for selecting among the solutions produced by this algorithm a partition whose isolated regions have a minimum, or a quasi-minimum, number of interconnections.

Session 10, Paper 10.1

THE SYNTHESIS OF NARROWBAND CRYSTAL BAND-ELIMINATION FILTERS

G. Szentirmai
Bell Telephone Laboratories

A new design theory is developed for the insertion loss synthesis of narrowband crystal band elimination filters. The theory is based on the narrowband approximation and consequent pseudo-reactance theory originally suggested by Baum and extensively used for narrowband bandpass filter design.

The structure used is a tandem connection of bridged-T sections, able to accommodate arbitrary crystal capacitance ratios and, through the use of a transformer, arbitrary crystal inductances. An additional free parameter can be used to reduce the spread of element values. An example illustrates the excellent agreement between approximate theory and exact final analysis.

Session 10, Paper 10.2

A LOWPASS TO BANDPASS TRANSFORMATION FOR PASSIVE AND ACTIVE RC FILTERS

Bengt T. Henoch
The Royal Institute of Technology, Sweden

A lowpass to bandpass transformation of the form $\gamma=s+\frac{\omega_0^2}{s}+2\omega_0$ is derived for dimensionless transfer functions of RC networks. Synthesis in a complex γ-plane is used to design several passive and active RC filters and the general limitations inherent in RC bandpass filters are discussed in terms of the transform. It is shown that use of the transform leads to canonical filter circuits and that the lay cut of the filter elements can simplify the manufacture by using lossy dielectrics or the diffusion factor in special transistors. When using the special transistors with a chosen diffusion factor it is also possible to extend the transform to the synthesis of one-part RC networks. The derived bandpass transform is also given in a generalized form applicable to distributed RC networks. The pole position sensitivity of active RC bandpass filters synthesized according to the transform is discussed and design criteria for minimum-sensitivity circuits containing two active elements are given. Using the transform an equivalent Q-value of 1/2 is defined for RC networks and when comparing with the Q-value of LC networks it follows that inductors with Q-values higher than 1/2 will give networks superior to RC networks.

Session 10, Paper 10.3*

THE GENERALIZED INVERSE IN NETWORK ANALYSIS AND QUADRATIC ERROR MINIMIZATION PROBLEMS

R. K. Manherz and S. L. Hakimi
Northwestern University

Basic properties of generalized matrix inverses are utilized to simplify a class of network analysis problems by providing a method for systematically eliminating unwanted variables from systems of complex linear algebraic equations. This result taken together with methods presented for minimizing general quadratic forms subject to linear constraints provide techniques for solving a variety of quadratic error minimization problems.

This work was supported by the Air Force Office of Scientific Research under Grant AF-AFOSR-98-67.

Session 10, Paper 10.4*

NETWORK FUNCTION DETERMINATION FROM PARTIAL SPECIFICATIONS

A. R. Braun and E. L. McMahon
University of Michigan

The j-axis real and imaginary parts of a function analytic in the closed right half plane are related by the Hilbert Transform, one form of which is

$$f(\omega) = \frac{\pi R(\omega)}{2\sqrt{1-\omega^2}} + \int_0^1 \frac{\lambda X(\lambda)\,d\lambda}{(\lambda^2-\omega^2)\sqrt{1-\lambda^2}} = \int_1^\infty \frac{\lambda R(\lambda)\,d\lambda}{(\lambda^2-\omega^2)\sqrt{\lambda^2-1}} \quad ,0\le\omega\le1$$

If $R(\omega)$ and $X(\omega)$ are known for $\omega\in(0,1)$, the left side of this equation is known. $R(\omega)$ for $\omega\in(1,\infty)$ can be found by making the change of variable $\lambda=\sec \phi/2$ and expanding both sides in a power series

$$f(\omega) = \sum_{n=0}^{\infty} K_n \omega^{2n} = \frac{1}{2} \sum_{n=0}^{\infty} \omega^{2n} \int_0^\pi R^*(\phi)\cos^{2n}\frac{\phi}{2}\,d\phi$$

Expanding $R^*(\phi)$ in a Fourier series, $R^*(\phi)= \sum_{k=0}^{\infty} A_k \cos k\phi$,

and using the identity $\cos^{2n}\frac{\phi}{2} = \sum_{m=0}^{n} B_{nm}\cos(n-m)\phi$

one obtains

$$K_n = \frac{1}{2} \sum_{m=0}^{n} B_{nm} \sum_{k=0}^{\infty} A_k \int_0^\pi \cos k\phi\cos(n-m)\phi d\phi = \frac{\pi}{2^{2n+1}} \sum_{m=0}^{n} A_{(n-m)} \binom{2n}{m},$$

which can be solved recursively for the A_k's, thus determining $R(\omega)$ for $\omega\in(1,\infty)$. A similar procedure can be used for $X(\omega)$.

When $R(\omega)$ and $X(\omega)$ on $(0,1)$ are given numerically, a technique is given for finding the power-series expansion of $f(\omega)$ by means of a Fourier expansion. An example is given, showing good convergence properties and excellent agreement with theory.

Session 10, Paper 10.5*

SOME SURPRISING RESULTS IN THE THEORY OF OPTIMUM BROADBAND MATCHING

Walter H. Ku
Sylvania Electronic Systems

This short paper presents some rather surprising results in the theory of optimum broadband matching. It is shown that for broadband matching of a simple shunt RC or series RL load with the class of Butterworth responses, there exists an optimum gain-bandwidth product which is attained by Butterworth response of finite degree, n*. Furthermore, this optimum exceeds the limiting value predicted by the classical Bode-Fano broadband matching theory. Similar results are obtained for the class of Chebyshev responses. Finally, it is shown that although these results are somewhat unexpected they do not by any means contradict the validity of the classical broadband matching theory. The apparent paradox can be explained by the fact that the gain and bandwidth parameters are often arbitrarily chosen for convenience and the conventionally defined gain-bandwidth products sometimes do not represent meaningful performance criteria of the matching network.

Session 10, Paper 10.6*

ON THE SOLUTION OF THE GENERAL LINEAR NETWORK

Hector Arango
Universidad Nacional del Sur, Argentina

Ordinary methods of network analysis require an incipient stage of organization in the connection of passive elements and sources. In fact, the network must be decomposable in a class of basic subnetworks consisting in one finite impedance (or admittance), a series voltage source and a parallel current source.

Therefore, undecomposable connections of immittances and sources must be previously modified to equivalent decomposable connections. Here it is proposed a transformation method that can be applied to any physically possible network. Such method can be algebraically expressed in a rather simple way.

The equivalence between original and modified circuit is proved, and an example of the transformation technique is outlined.

Session 10, Paper 10.7

A CONSTRUCTIVE GRAPH-THEORETIC SOLUTION OF THE SHANNON SWITCHING GAME

J. Bruno
Princeton University

L. Weinberg
City College of New York

A simple solution of the two-person switching game is given. This solution is a completely graph-theoretic one. It makes use of the theory of the principal partition of a graph, which had originally been put forward in connection with more efficient schemes for network analysis. The solution leads to a set of strategies which are simple to program on a digital computer. In these strategies it is required that a 2-maximally distant forest pair (or coforest pair) of the given graph be known so that the principal partition can then be determined. It is shown that the principal partition immediately determines the type of game--short, cut or neutral--to be played on the graph; this constitutes a new result.

In presenting the results, the duality concept in graphs is described and applied. It is shown, for example, that the cut game and the short game are completely dual. Neither is simpler than the other. It is also shown that a global strategy exists not only for the short game but for all games. It is emphasized in the paper that the duality concept gives significant information about one and the same graph, independent of its planarity. The existence of a dual graph has often been allowed to obscure the more general duality concept.

Special Session 3, Paper S3.1

DIGITAL INTEGRATED CIRCUIT COMPUTER-AIDED DESIGN DILEMMAS

Ronald A. Rohrer
Fairchild Semiconductor

With models and methods far too general for the situations that arise, the network theorists must learn to exploit thoroughly their narrow range of characteristics to cope successfully with digital integrated circuits. In particular, network theorists might do well to reexamine some of the current cliches of nonlinear network theory in the light of the realities of nonlinear network practice.

State equations are a convenient vehicle for the discussion in general of nonlinear networks, but some of the most interesting switching circuits exhibit nonunique solutions--and still must be analyzed! The Newton-Raphson method exhibits quadratic convergence (when it works), but quite frequently fails in the face of diode exponential nonlinearities--virtually the only kind encountered! Controlled source models of active coupling devices may be theoretically satisfying, but rarely correspond to laboratory data or efficient computer simulation of related circuit behavior.

Increased cognizance of computer capabilities may be the key to effectiveness in digital integrated circuit design efforts.

Special Session 3, Paper S3.2

THE SYNTHESIS OF HIGH FREQUENCY TRANSMISSION ZERO FILTERS WITH A ONE-POLE INTEGRATED GAIN BLOCK

W. R. Broyles

This presentation is intended to illustrate the need for synthesis techniques which utilize models that are compatible with present state of the art integrated circuit devices.

Transmission zero filters produced with conventional operational amplifiers and RC embedding networks are limited to a cutoff frequency of approximately 100 KHz. This paper describes the synthesis of high frequency (above 1 MHz) transmission zero filters, achieved by replacing the operational amplifier with an integrated high frequency gain block, which may be modeled as a one-pole device. The location of the gain block pole is a variable which may be controlled by external narrowbanding techniques.

Designs using two specific RC embedding networks are presented to indicate how parameters which are an integral part of manufacturable devices may be incorporated into the synthesis procedure. In particular, the inherent pole of the gain block is used to produce prescribed frequency characteristics. The effects of finite input impedance and non-zero output impedance of the gain block on the overall design are also discussed.

Special Session 3, Paper S3.3

LARGE-SIGNAL CHARACTERIZATION OF INTEGRATED CIRCUITS

Fred A. Lindholm
University of Florida

In the design of integrated circuits, modeling takes a central role, for it is modeling that supplies the designer the basic describing equations he manipulates to achieve a desired circuit function.

This paper describes two general approaches useful in the modeling of integrated circuits and illustrates their utility by applying them to integrated bipolar and field-effect transistors. The examples chosen concentrate on the derivation of large-signal (nonlinear) characterizations, such as are needed in the design of digital systems, though concomitant linear characterizations result when the constraint of small-signal excitation is imposed.

The characterizations (or models) are intended to be useful for both device design and circuit design. Their parameters can be determined by two alternative means: either by a set of measurements made at the terminals, which is a property essential for circuit design, or by the determination of the structural and material constants of the integrated circuit, which aids device design. To make available the vast store of techniques and results of lumped network theory, the models are formulated in terms of ordinary differential equations, the same sort of equations as that describing lumped electric networks.

The first of the general modeling approaches to be described employs the Laplace transform to remove functional dependence on spatial coordinates, thus yielding ordinary differential equations in the independent variable time. Application to the integrated bipolar transistor illustrates the use of this approach. The resulting characterization, which is in the form of a 3x3 matrix, reveals and sets forth quantitatively the interaction of the substrate-collector junction, the existence of which distinguishes integrated from discrete transistors. By employing a generalization of this first modeling approach one can account for three-dimensional current flow within the device, though at the expense of greatly increased complexity. This is briefly discussed.

The second general approach utilizes certain measures of the static performance to derive a characterization of the dynamic performance. In illustration, it is applied to integrated field-effect transistors of both the MOS and junction-gate types.

Session 11, Paper 11.1

THE K-MATRIX OF N-PORT NETWORKS: ANALYSIS AND SYNTHESIS

A. Lempel and I. Cederbaum
Technion, Israel

A new characterization of the terminal behaviour of linear n-port networks by means of an (nxn) matrix K is proposed. The conventional role of ports is preserved here only in looking on them as the sole input gates of the network, whereas any pair of terminals is admissible for output specifications.

This new characterization is shown to be a convenient medium in analysis of a general linear n-port network. More important, in the case of a real matrix K, the paper provides an algorithm which either leads to a realization of a resistive n-port network complying with the given specification or shows that such a realization does not exist.

The algorithm consists of two steps. In the first step, the port-graph is uniquely determined. In the second one a finite number of linear programs are solved. In the realizable case the solution provides directly the values of all the network elements.

Session 11, Paper 11.2

THE THEORY OF GENERALIZED INTERDIGITAL NETWORKS

J. David Rhodes
Microwave Development Laboratories

A theory for two-port interdigital networks is presented. Initially, after the definition of an arbitrary interdigital network, properties of admittance scaling and transformations of general interdigital lines are formulated. The necessary and sufficient conditions are then determined for the individual realization of any admittance parameter of a two-port interdigital network. The results obtained in this section influence the choice of a compact set of sufficiency conditions for the realization of any arbitrary two-port admittance matrix by an interdigital network. These sufficiency conditions are also shown to imply a simple sufficiency condition on the insertion-loss function of a resistively terminated, two-port interdigital network.

Finally, as an example of the synthesis procedures used to demonstrate sufficiency, a broad-band, maximally flat, linear phase, microwave filter or transformer is realized by an interdigital network.

Session 11, Paper 11.3*

TRANSFORMERLESS 2n-PORTS WITH DIRECTIONAL COUPLING

P. M. Lin
Purdue University

This paper presents a class of transformerless 2n-ports with the following three properties: (1) With each port terminated in a resistance R, matched conditions exist at all ports and at all frequencies. (2) There exists no coupling between any two ports numbered 1 through n, and neither between any two ports numbered n+1 through 2n. (3) The transfer function between any one of the ports numbered 1 through n and any one of the ports numbered n+1 through 2n is not identically zero.

Concepts in network topology play an important role in arriving at the three properties stated above. Transfer functions among coupled ports are derived through the use of a result due to Feldtkeller. The application of these 2n-ports as signal splitters is discussed.

Session 11, Paper 11.4*

ON SCATTERING MATRICES NORMALIZED TO ACTIVE n-PORTS AT REAL FREQUENCIES

M. R. Wohlers
Grumman Aircraft

This paper extends the complex normalization techniques developed by Youla and Rohrer to allow for a normalization to arbitrary constant nxn matrices. The technique developed is predicated on the assumption that one wishes to preserve those properties of the scattering matrix that prove most useful in the study of passive matching networks. The discussion includes an application of the technique to the real-frequency design of maximum gain amplifiers using a single two-port active element imbedded in a passive coupling structure.

Session 11, Paper 11.5

COMPUTER GENERATION OF TREES AND COTREES IN A CASCADE OF N-PORT NETWORKS

Wai-Kai Chen
Ohio University

Generation formulas from which the sets of trees and cotrees in a cascade of arbitrary passive n-port networks not containing mutual inductances are given in terms of the ring-sums or the unions of the Cartesian products of the sets of subgraphs of the component networks are presented. If the subgraphs of the component networks are given, the proceudre will not generate any duplications, redundancies or cancellations of terms. Methods of generating certain types of desired subgraphs of the component networks and illustrative examples are also given.

Session 12, Paper 12.1

STABILITY PROPERTIES OF SHAPING FILTERS

L. H. Brandenburg and H. E. Meadows
Columbia University

A shaping filter is a linear system which transforms stationary white noise into a possible nonstationary random process having a given covariance $r(t,\tau)$. We show that stability of a shaping filter, appropriately defined, may be determined by inspection of $r(t,\tau)$. Stability is defined in the sense that any square-integrable input produces a bounded output (abbreviated L_2IBO).

The following results are proved:

1. A system with impulse response $h(t,\tau)$ is L_2IBO stable if and only if $\int_{t_0}^{t} h^2(t,\tau)d\tau \leq C < \infty$ for all $t \geq t_0$; t_0 is a fixed intial time (perhaps $-\infty$).

2. If $r(t,t) \leq C < \infty$ for all $t \geq t_0$, the shaping filter is L_2IBO stable.

3. (Converse to 2) If the shaping filter is (uniformly) completely controllable, L_2IBO stability implies that $r(t,t) \leq C < \infty$ for $-\infty$ ($\leq$) $< t_0 \leq t$.

Also included in the hypotheses of 3 is an assumption to the effect that the system is internally linear. The results of the paper apply to distributed as well as lumped systems. Detailed knowledge of the impulse response (or state-variable equations) is not required.

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Session 12, Paper 12.2*

STABILITIES OF LINEAR AND NONLINEAR NETWORKS

Ruey-wen Liu
University of Notre Dame

Two classes of networks are considered: passive networks and two-element-kind-networks. Necessary and sufficient conditions for asymptotic stability are obtained for each case. These conditions can be tested by inspection. The convergence of solutions and the existence of a periodic steady-state solution of forced networks are also considered. A novel point in the approach to the stability problems is that it is carried out in terms of a component-connection model instead of a state model.

Session 11, Paper 11.6

THE MODIFIED CIRCUIT MATRIX OF AN n-PORT NETWORK AND ITS APPLICATIONS

K. Thulasiraman and V. G. K. Murti
Indian Institute of Technology, India

Certain properties of the modified circuit matrix useful in the analysis and synthesis of n-port networks are outlined. A sufficient condition based on the modified circuit matrix is given for the proper pseudo-series connection of n-port networks. The usefullness of the concept of the modified circuit matrix in synthesis of networks is demonstrated by giving a new approach to the realization of 2-element-kind 2-port networks.

Session 11, Paper 11.7*

THE PROJECTION THEOREM FOR HYPER ACUTE ANGLED SIMPLICES IN EUCLIDEAN SPACE E_m AND ITS APPLICATION TO THE PARAMOUNT CONDITION OF RESISTIVE N-PORTS

D. J. H. Moore and Gerald E. Subak-Sharpe
City College of New York

An (m+1)-terminal resistive network may be represented as an hyperacute angled simplex (H.A.A.) P_m in m-dimensional euclidean space E_m. A simplex is H.A.A. if all its first and higher order angles are acute.

Several lemmas on the vertices of such simplices are given and in particular we establish the necessary and sufficient conditions for a vertex q to be inside the simplex with vertices 1,2,...q-1, q+1...m+1. Hence follows the main theorem, called by us the projection theorem of H.A.A. simplices.

Because a resistive n-port ($n \leq m \leq 2n-1$) may be inscribed on (m+1)-terminals (vertices), the projection theorem allows a simple geometric interpretation of the paramount condition, which is discussed. Since this condition is known to be necessary but insufficient for the realization of n-port Z matrices the approach presented here is valuable, because it reduces the n-port problem to the solution of a geometric problem in m-dimensional euclidean space.

Session 12, Paper 12.3

STABILITY RESULTS FOR A CLASS OF DISTRIBUTED PARAMETER NETWORKS AND SYSTEMS

Rui J. P. de Figueiredo and K. S. Chao*
Rice University

A number of stability results for general systems of linear and nonlinear partial differential equations that describe distributed parameter networks and system are obtained by means of Liapunov's direct method.

Conditions for the asymptotic stability of the null solution of linear time-invariant distributed parameter systems are given. This result is then extended to a class of distributed parameter systems consisting of a linear system and a zero memory nonlinear element, described by a set of Lurie-like partial differential equations.

Bounded input-bounded output stability for the above two classes of systems is established by extension of a result of Goldwyn, Chao and Chang for lumped parameter systems. Finally, it is shown how Malkin's theorem on the stability under persistent disturbances can be extended so as to provide a solution to the dynamic range problem for systems described by a general set of nonlinear partial differential equations.

This work was supported by the National Science Foundation under Grant GU-1153.

*Now with Texas Technological College.

Session 12, Paper 12.4

STABILITY OF WAVEFORMS ON ACTIVE NONLINEAR TRANSMISSION LINES

Allen G. Lindgren and Richard J. Buratti
University of Rhode Island

Steady propagation on the tapered RC±G and RLC±G nonlinear transmission lines is investigated and the existence of "pulse", "change of state", and periodic waveforms is predicted for both lines. These neuristor waveforms have the property of propagating at a constant velocity without attenuation or distortion. A stability analysis, employing a generalization of the direct method of Liapunov, reveals that a predicted waveform is stable if its derivative is the minimum eigenvalue solution of the linearized system equations for perturbations about the steady waveform. The stability of these distributed systems is, therefore, reduced to the Sturm-Liouville problem of determining the eigensolution dependence on boundary conditions.

Similar to the behavior of ordinary [discrete] systems, it is shown that for positive eigenvalues [$\lambda>0$], stability of the linearized distributed system implies stability of the nonlinear system for sufficiently small perturbations. For $\lambda=0$, the linear approximation normally falis and stability is found to depend on the system nonlinearities. In the problem considered, the derivative of the steady waveform always represents the zero value eigensolution which produces the cirtical stability case. However, in this paper, it is shown that the zero eigenvalue solution can be removed from any given per bation by an appropriate shifting of the steady inherent waveform. Therefore, if the derivative of the neuristor waveform, which is the $\lambda=0$ eigensolution, is the minimum eigensolution of the linearized system, then the waveform is stable. For the lines considered, this implies that the "change of state" waveform is stable while the "pulse" waveform is unstable.

Session 12, Paper 12.5

TWIN-T DESIGN FOR CONTROLLED ZERO SENSITIVITY AND STABILITY IN LINEAR ACTIVE NETWORKS

G. S. Moschytz
Bell Telephone Laboratories

Design equations are presented providing twin-T configurations with controlled zero sensitivity. Three special cases are considered that are useful in linear active networks incorporating a twin-T in the feedback path. The first provides zero shift along the jω-axis, the second zero shift parallel to the real axis with variations of one component only. The third investigates the possibility of orthogonal sensitivity functions. Design examples are given. Measurements demonstrate the effectiveness of the given design equations.

Limits on the permissible null depth of a twin-T are derived for the case that left-half plane zeros must be guaranteed under worst case component drift conditions. Similarly expressions are derived that permit the limits of resistor and capacitor temperature coefficients and aging characteristics to be established in order not to exceed a given maximum frequency drift of the transmission zero. A numerical example is given using the characteristics of tantalum thin film resistors and capacitors.

Session 12, Paper 12.6*

STABILITY CRITERIA OF LINEAR ACTIVE NETWORKS WITH IMBEDDED NEGATIVE RESISTANCE ELEMENTS

Walter H. Ku
Sylvania Electronic Systems

This paper presents some results on the stability of linear active networks containing an arbitrary number of negative resistance elements. Explicit stability criteria are derived for several general calsses of active networks. Particular attention is concentrated on specific active arrya applications in which the active components are unstable negative resistance elements such as tunnel and avalanche diodes and the passive imbedding network is an antenna array structure. The effect of antenna mutual coupling on the stability of linear and planar active arrays has been studied in some detail. Explicit stability criteria for various active Van Atta arrays using bilateral and unilateral amplification in the antenna interconnecting delay path are derived in the paper. Based on these stability criteria, definitive results are obtained concerning the limitations and various tradeoffs relating the size and configuration of the array, the amount of mutual coupling, the parameters of the negative resistance elements, and the gain of the system. The effect of nonideal coupling networks such as hybrids and circulators has also been studied.

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Panel Discussion

FUTURE RESEARCH DIRECTIONS IN CIRCUIT THEORY

Moderator: M. E. Van Valkenburg, Princeton University

Panelists: H. J. Carlin, Cornell University

E. S. Kuh, University of California, Berkeley

J. A. Narud, Motorola

G. C. Temes, Ampex Corporation

List of Summaries Not Included in this Digest

The summaries of the following papers are not available at the time of the publication of this Symposium Digest:

Session 4

Paper 4.4 "Intermodulation Improvement in a Semiconductor Diode Junction", W. R. Gretsch, Westinghouse Electric Corporation.

Paper 4.6 "Synthesis of Grounded Active RC N-Ports with Prescribed Range of Element Values", M. Goldman and M. S. Ghausi, New York University.

Session 5

Paper 5.5 "Commensurate Multilayer Distributed RC Networks", J. O. Scanlan and N. Ramamurty, University of Leeds, Great Britain.

Session 9

Paper 9.6 "Unijunction Transistor Model for Computer Circuit Analysis", M. E. Daniel, Sandia Laboratory.

Special Session 3

Paper S3.4 "Semiconductor Integrated Memories", H. C. Lin, Westinghouse Electric Corporation.

Paper S3.5 "High Poser Integrated Amplifiers".

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