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Generic Approaches to the Design of Network Services Circuits

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This paper describes recent developments in modeling and analysis tools that are basic to a generic approach to the design of network services circuits for voiceband applications. Providing network services is a major part of the effort to support the tactical needs of telecommunications users. The design of network services circuits is the process of choosing configurations of transmission facilities and equipment for realizing circuits within appropriate performance specifications. Techniques for design have been developed under the general heading of "standard designs" and, until recently, have largely taken their structure from the capabilities of specific equipment.

I. INTRODUCTION

Providing public switched services constitutes a major part of the telecommunications industry. These services, collectively referred to as plain old telephone service (POTS), are provided over the public switched telecommunications network to residential and business customers. Another segment of this industry involves the offering of special services. A customer service is termed a special service if it requires special procedures and/or equipment for design, installation, or maintenance as compared to POTS. Special services provide arrangements and features that are not ordinarily available in the public network. They are generally provided to business customers by a

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variety of facilities such as dedicated private communication lines, switched-service arrangements and adjuncts to POTS. Figure 1 illustrates some typical special services circuits.

We refer to POTS and special services collectively as network services. The design of network services circuits is one of the major processes in the provisioning of these services. It involves the selection of proper transmission facilities as well as the selection and placement of necessary network equipment so that the resulting circuit meets all transmission and signaling requirements. In the case of special services circuits, the design is more complicated because, generally, such circuits have more stringent transmission and signaling requirements than POTS circuits. However, they must be built from communication facilities often intended for POTS.

Most network services are extended to customers' premises over a network of transmission facilities referred to as the loop plant. This network is constructed to serve large local areas. Thus, especially in analog voice transmission, a large variation exists in the transmission characteristics of the loops.[1] This further complicates the design of network services circuits, particularly special services circuits where

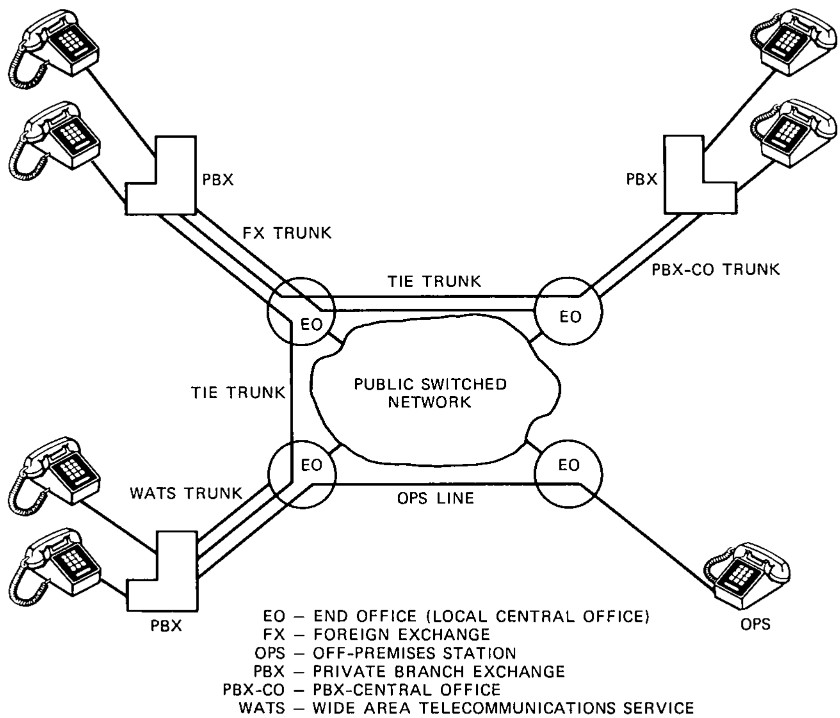


Fig. 1—Typical special services circuits.

the transmission characteristics of each link in the circuit must be tightly controlled so that the transmission requirements (such as loss, attenuation distortion, echo, and noise) in the overall circuit are kept within acceptable bounds.[2]

The general steps in the design of a network services circuit are as follows:

1. Selection of loop facilities (if any)
2. Selection of interoffice transmission facilities (i.e., routing)
3. Selection of design architecture
4. Selection of network equipment
5. Setting network equipment (i.e., adjusting equipment parameters to proper values)
6. Validation of the circuit (i.e., making sure that the circuit meets all transmission and signaling requirements).

Standard methods have been developed for the design of network services circuits.[3–5] These methods, referred to as standard design procedures, are sets of guidelines and algorithms that enable the designer to perform the above steps in the design systematically. To date, however, these procedures have been heavily dependent on the capabilities of specific network equipment rather than on their functions. That is, the procedures assume that only certain specific equipment items, whose characterizations have been stored, can be used in the design. The drawback of this is that whenever a new piece of equipment is developed, design procedures must be revised in order to incorporate it into the circuit design process. This often causes a considerable time lag between the availability of a new piece of equipment and its incorporation into the design.

To alleviate these shortcomings, a generic design concept must be developed. Such a design concept would be based on the functional features of equipment items rather than their specific technology. We discuss the generic design concept in Section II, where we also identify the theoretical basis required for the realization of the generic design process. The remainder of the paper is concerned with developing this theoretical basis. Equipment models are discussed in Section III. An analysis tool which can be used to standardize various equipment requirements in network services circuits is presented in Section IV. An illustrative example is taken up in Section III and is followed through in Section IV. A glossary of terms used in the text with their definitions is given in Appendix A. The emphasis of the discussion is on the transmission aspects of voice-grade network services circuits.

II. THE GENERIC DESIGN CONCEPT

Generic design methods are based on the functional features of network equipment. Thus they remove the dependence of design on specific equipment technology. Steps in the generic design process include identification of appropriate facility/equipment configurations, development of standards for equipment functions, and determination of design objectives. The required subprocesses in the generic design process are listed below:

1. Estimation of equipment/facility performance capabilities
2. Definition and priority ordering of various design options (or strategies)
3. Determination of equipment/facility compatibility rules
4. Identification of various transmission/signaling options
5. Development of methods for performance validation (i.e., simulation)
6. Packaging and deployment of methods (e.g., software development).

Figure 2 shows the process flow in the provisioning of network services circuits. The top part of this figure (Databases) shows various databases that contain information about transmission facilities and equipment as well as design architectures and design objectives. The boxes in the middle row of this figure (Design Steps) show the tasks that have to be performed by the circuit designer. They start with the Service Order and culminate in the Circuit Work Order (used by the installers). Cumulative outputs of the design processes are shown above these boxes. The bottom row of Fig. 2 (Design Algorithms) shows various algorithms needed to perform the design. The designer uses these algorithms in conjunction with the databases to perform the design steps. For example, the designer accesses the loop-inventory database and uses the loop-selection algorithm to implement the loop-selection step of the design, i.e., to select a loop (or loops) for the circuit being designed.

The generic design process has a hierarchical information structure. The top level of such a hierarchy contains robust constructs for network services circuits. In such constructs one deals with the features required of various equipment rather than their identities. Each equipment is represented by a feature code which is a collection of feature elements (such as gain and equalization) that provide the appropriate transmission and/or signaling treatment for the equipment's intended use in a circuit. To fully develop these constructs, models are needed for the equipment that can provide adequate and representative characterization of equipment behavior. In such models, referred to as generic equipment models, the primary characterization of equipment would be functional rather than physical. Specific equipment could be coupled into the generic design process by linking the equipment to feature codes through a validation step.

The lower levels of the information hierarchy further specify the

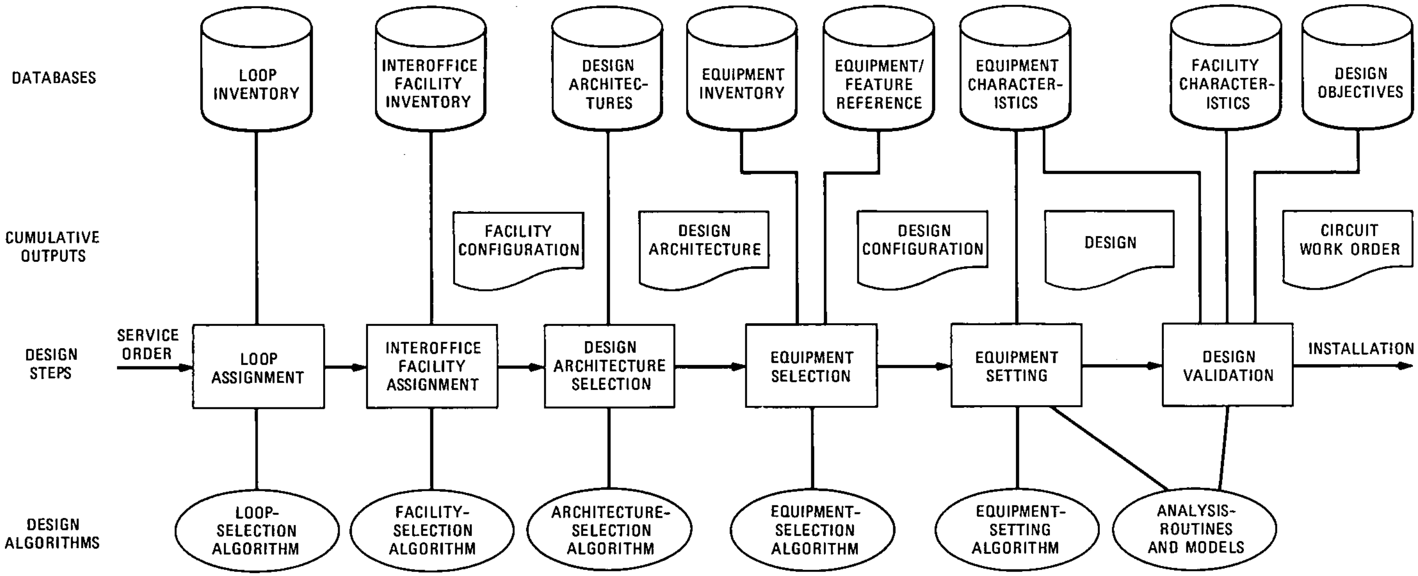


Fig. 2—Process flow in the provisioning of network services circuits.

requirements of the equipment in the circuit based on circuit configuration and service requirements. Thus the information hierarchy will be stable at the top level and only the lower levels may change due to equipment technology and type of service.

Another requirement of the generic design process is an analysis tool for evaluating various design strategies, determining equipment functional specifications, and predicting circuit performance. Such an analysis tool should be capable of simulating circuit performance based on nominal facility and eqiupment specifications. It should be able to evaluate the effects of variations in the transmission facility and equipment specifications due to manufacturing tolerances, quantization errors, temperature changes, aging, etc. The analysis tool would be used to determine correct bounds on the elements of equipment features in various design configurations. This, in turn, would allow the equipment to be categorized (or standardized) according to the bounds on the elements of their features.

The benefits of the generic design process can be summarized as follows:

1. It alleviates shortcomings in the application of the present design methods which are limited to specific network equipment. That is, it facilitates the incorporation of suitable new equipment into the circuit design process.

2. It promotes the standardization of equipment functions. This, in turn, can serve as guidelines for equipment developers.

3. It reduces the lead time required to incorporate new equipment into the circuit design process. Indeed, it enables parallel (rather than serial) interaction with the equipment developers.

4. It facilitates coordination of planning and provisioning.

We discuss equipment models in Section III. An analysis tool for the generic design process is presented in Section IV. Various information management tools would be needed to develop and deploy the generic design process. In this connection, some software tools have already been developed.[6] However, we are not concerned with this aspect of the generic design process here.

III. MODELS

A generic segment of a network services circuit is a portion of the circuit that can be functionally characterized apart from any specific equipment technology. For example, consider the network services circuit with the three 2-wire cable facilities and two repeaters shown in Fig. 3. Any facility alone, any repeater alone, or any repeater with one or two adjacent facilities can be considered as a generic segment. The models to be described in this section are for 2-wire to 2-wire, 2-wire to 4-wire (or 4-wire to 2-wire) and 4-wire to 4-wire generic

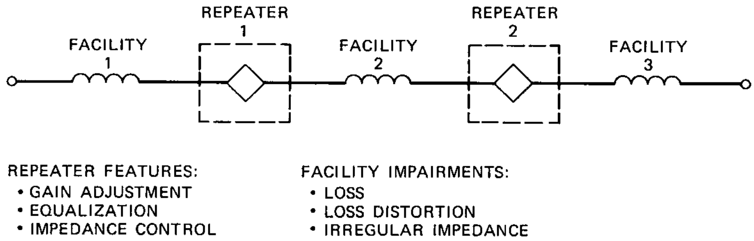


Fig. 3—A 2-wire voice-grade circuit.

segments. A generic equipment model is an equipment model in which primary characterization of the equipment is functional (e.g., transducer and return losses) rather than physical (e.g., resistors, inductors, and capacitors).

3.1 Equipment and facility considerations

As Fig. 3 indicates, the functional features of voice-grade network equipment are gain adjustment, equalization, and impedance control. The facility impairments to be considered in generic modeling are loss, loss (or attenuation) distortion, and irregular impedance. In developing generic equipment models, we consider the following generic segment measures: 1-kHz gain (or loss); gain-frequency response; 1-kHz phase delay; envelope delay distortion (EDD); and impedance control (return loss). Table I summarizes the generic segment measures.[7] Column 1 lists the generic segment measures; column 2 lists the parameter from which each measure is derived; column 3 lists the definition and the dimension of each measure; and column 4 lists the typical form of specification of each generic segment measure. For example, the 1-kHz gain is defined as 10 log[g_{vf}(1 kHz)], where g_{vf} is the forward voltage gain of the equipment. This measure is typically specified by a nominal value with symmetric tolerances as 3.5 ± 1.0 dB. The balance return loss and the structural return loss in Table I are typically specified by minimum and median weighted values.[8]

3.2 Parameterization

To represent a linear network, one can use any one of the following sets of parameters: the open-circuit impedance (or the z) parameters; the short-circuit admittance (or the y) parameters, the transmission (or the $ABCD$) parameters; the scattering (or the s) parameters, the hybrid (or the h) parameters. In this study we will use unnormalized voltage scattering parameters[9] to characterize a generic segment for the following two reasons. First, not all networks possess the z or the y parameters; however, any linear network can be represented by a scattering matrix. Second, most of the commonly used network func-

Table I—Generic segment measures, their derivatives, definitions, and typical specifications

Generic Segment Measure	Parameter Derived From	Definition and Dimension	Typical Form of Specification
1-kHz gain	Forward gain g_{vf} Reverse gain g_{vr}	$10 \log[g_v(1 \text{ kHz})]$ Decibels (see note 1)	Nominal value with symmetric tolerances
Gain-frequency response	Forward gain g_{vf} Reverse gain g_{vr}	$10 \log[g_v(f)]$ Decibels (see note 1)	Template over band 400–2800 Hz and referenced to 1 kHz
Phase delay	Forward gain g_{vf} Reverse gain g_{vr}	$T_p(1 \text{ kHz})$ Microseconds (see note 2)	Maximum value at 1 kHz
Envelope delay distortion	Forward gain g_{vf} Reverse gain g_{vr}	$T_e(f) - T_e(f_{ref})$ Microseconds (see note 3)	Maximum difference of envelope delay between any two frequencies over 500–3000 Hz band
Balance return loss	Input: Balance reflection coefficient δ_1 Output: Balance reflection coefficient δ_2	$-20 \log[\lvert\delta_1\rvert]$ Decibels	Minimum weighted values; e.g., echo and singing (high and low) return loss
Structural return loss	Input: Structural reflection coefficient ρ_{11} Output: Structural reflection coefficient ρ_{22}	$-20 \log[\lvert\rho_{11}\rvert]$ Decibels	Minimum weighted values

1. g_v (equipment voltage gain) can be g_{vf} or g_{vr}
2. $T_p(f) = -\frac{1}{\omega} \arg(s_{21})$
3. $T_e(f) = \frac{d}{d\omega} [-\omega \cdot \arg(s_{21})]$

tions, e.g. the input and the output impedances, the transducer loss, the return loss, and so on, can be easily related to the scattering parameters (i.e., the elements of the scattering matrix).

As an example consider a 2-wire generic segment, a 2-port network, which is represented by a 2×2 scattering matrix $\{s_{ij}\}$, $i, j = 1, 2$. It can be easily shown that the input and output impedances are given by[7]

$$Z_{\text{in}} = \frac{1 + s_{11}}{1 - s_{11}} Z_{01} \tag{1}$$

$$Z_{\text{out}} = \frac{1 + s_{22}}{1 - s_{22}} Z_{02}, \tag{2}$$

where Z_{0i} $(i = 1, 2)$ is the impedance seen looking from the repeater into facility i with a resistive termination (nominally 600 or 900 ohms). Also the forward transducer gain is given by[7]

$$tg_f = \frac{\mathrm{Re}(Z_{01})\mathrm{Re}(Z_{02})}{|Z_{02}|^2}\,|s_{21}|^2, \tag{3}$$

and the reverse transducer gain is given by

$$tg_r = \frac{\mathrm{Re}(Z_{01})\mathrm{Re}(Z_{02})}{|Z_{01}|^2}\,|s_{12}|^2. \tag{4}$$

The return loss RL_i ($i = 1, 2$) at port i can be shown to be[7]

$$RL_i = -20 \log |s_{ii}|. \tag{5}$$

One can see that the s parameters (i.e., s_{11}, s_{12}, s_{21}, and s_{22}) of a 2-wire generic segment can be obtained from these network functions. It should be mentioned that an input reference impedance and an output reference impedance are required in order to represent a linear 2-port network by a scattering matrix.[9] In this study, Z_{01} and Z_{02} represent the input and the output reference impedances (see Fig. 4).

3.3 Reference environments

There are two reference environments that are commonly used to specify transmission performance measures: (1) the driving-point (or impedance control) environment, and (2) the gain-loss related environment. The development of generic equipment models is based on these two environments. However, the final model is characterized in the gain-loss related environment.

The impedance control measures, such as the structural return loss,[8] balance return loss, and equal-level echo path loss (ELEPL),[7] are specified in the driving-point environment. The 1-kHz loss, the gain-frequency response, the phase delay and the envelope delay distortion (Table I) are specified in the gain-loss related environment.

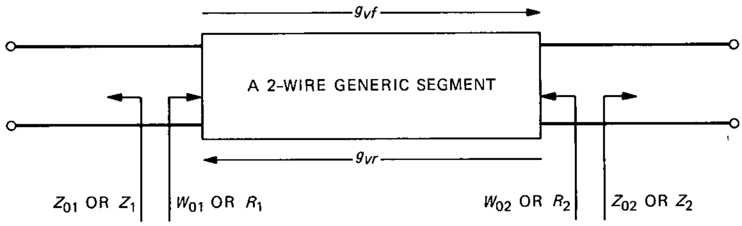
The reference impedances in the gain-loss related environment are called the primary input and output reference impedance (Fig. 4). Those in the driving-point environment are called the secondary reference impedances.

3.4 Gain definition

The following approximation has been widely used by network services circuit design engineers: *the end-to-end circuit transducer loss is equal to the sum of the facility transducer losses minus repeater gains.* For a 2-wire network services circuit with only one repeater, the statement becomes valid if the following definition for forward repeater voltage gain is adopted for a repeater:[7]

$$g_{vf} = \frac{s_{21}}{(1 + \alpha_1)(1 - \alpha_2)}\,\sqrt{R_1/R_2}, \tag{6}$$

where



BASIC PARAMETERS:

Z_{01}/Z_{02} = primary input/output references impedances
Z_1/Z_2 = secondary input/output reference impedances
W_{01}/W_{02} = nominal input/output impedances
R_1/R_2 = nominal input/output resistances
ρ_{11}/ρ_{22} = input/output structural reflection coefficients
δ_1/δ_2 = input/output balance reflection coefficients
g_{vf}/g_{vf} = forward/reverse voltage gain

DEFINED AND DERIVED PARAMETERS:

$$\eta_i = \frac{W_{oi} - Z_{oi}}{W_{oi} + Z_{oi}}; \; \gamma_i = \frac{Z_i - Z_{oi}}{Z_i + Z_{oi}}; \; \alpha_i = \frac{R_i - Z_{oi}}{R_i + Z_{oi}}$$

$$\hat{s}_{11} = \frac{\eta_i + \rho_{ii}}{1 + \eta_i \rho_{ii}}; \; \gamma_{ib} = \frac{\gamma_i + \delta_i}{1 + \gamma_i \delta_i}; \; (i = 1, 2)$$

Fig. 4—A 2-wire generic segment and its associated parameters.

$$\alpha_i = \frac{R_i - Z_{0i}}{R_i + Z_{0i}}, \qquad i = 1, 2, \tag{7}$$

$Z_{01}(Z_{02})$ is the primary input (output) reference impedance, and R_i is the nominal input ($i = 1$) or the nominal output ($i = 2$) resistance.[7] R_1 and R_2 are often associated with the generic segment in the gain-loss environment. They are used for purposes of gain administration. They do not represent the true input and output resistances. For a circuit with two repeaters (Fig. 3), even with the gain definition given in eq. (6) the statement given earlier in this section is not precise any more. Section 3.7 will discuss this in detail.

A generic equipment model, for a 2-wire generic segment, reflecting common performance measures, has been developed based on the gain definition given in eq. (6). This model is represented by the following 2×2 scattering matrix:

$$\{s_{ij}\} = \begin{bmatrix} \hat{s}_{11} + \dfrac{1 - \gamma_{1b}\hat{s}_{11}}{2\gamma_{1b}} [1 - \sqrt{1 + x}] & g_{vr}(1 + a_2) \\ \quad \cdot (1 - a_1)\sqrt{R_1/R_2} & \\ g_{vf}(1 + a_1)(1 - a_2)\sqrt{R_2/R_1} & \hat{s}_{22} + \dfrac{1 - \gamma_{2b}\hat{s}_{22}}{2\gamma_{2b}} \\ \quad \cdot [1 - \sqrt{1 + x}] & \end{bmatrix}, \tag{8a}$$

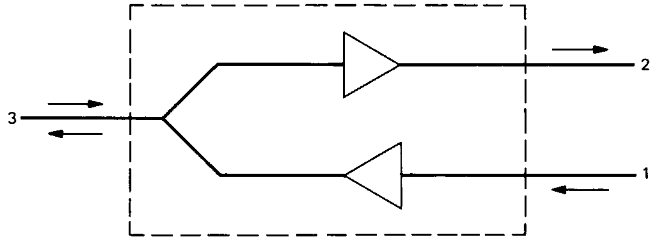


Fig. 5—A 4-wire to 2-wire (or 2-wire to 4-wire) generic segment.

where $\hat{s}_{ii}$, γ_{ib}, $i = 1, 2$, g_{vf}, and g_{vr} are defined in Fig. 4 and

$$x = \frac{4\gamma_{1b}\gamma_{2b}s_{12}s_{21}}{(1 - \gamma_{1b}\hat{s}_{11})(1 - \gamma_{2b}\hat{s}_{22})}. \tag{8b}$$

Detailed information on this 2-wire model can be found in Ref. 7.

3.5 Two-wire to four-wire and four-wire to four-wire segments

In this section we first describe the model of a 4-wire to 2-wire (or 2-wire to 4-wire) generic segment (Fig. 5). The "receive" path is designated as port 1, the "transmit" path as port 2, and the 2-wire port as port 3. The segment can be represented by a 3 × 3 scattering matrix.

In most applications of interest, we can assume that both the transmit and the receive paths are unidirectional. This assumption results in three zero elements: $s_{12} = s_{13} = 0$. Thus, the resulting scattering matrix becomes

$$\{s_{ij}\} = \begin{bmatrix} s_{11} & 0 & 0 \\ s_{21} & s_{22} & s_{23} \\ s_{31} & 0 & s_{33} \end{bmatrix}. \tag{9}$$

Next, we will relate the matrix elements with the transmission performance measures. The diagonal elements are related to the return losses as follows:

$$s_{ii} = \rho_{ii} \quad (i = 1, 2) \tag{10}$$

and

$$s_{33} = \frac{\eta_3 + \rho_{33}}{1 + \eta_3\rho_{33}}, \tag{11}$$

where

$$\text{return loss at port } i = -20 \log|\rho_{ii}|, \tag{12}$$

$$\eta_3 = \frac{W_{03} - Z_{03}}{W_{03} + Z_{03}}, \tag{13}$$

and Z_{03} is the primary reference impedance at port 3 while W_{03} is the nominal input impedance at port 3.

The transmit path voltage gain, g_{23}, is related to s_{23} as follows:

$$s_{23} = g_{23}(1 + \alpha_3)\sqrt{R_1/R_3}, \tag{14}$$

where R_1 is the nominal resistance at port 1 or 2, R_3 is the nominal resistance at port 3,

$$\alpha_3 = \frac{W_{03} - Z_{03}}{W_{03} + Z_{03}}, \tag{15}$$

and g_{23} is the voltage gain from port 3 to port 2. The receive path voltage gain, g_{32}, is related to s_{31} as follows:

$$s_{31} = g_{32}(1 - \alpha_3)\sqrt{R_3/R_1}. \tag{16}$$

The element s_{21} can be obtained as follows. When port 3 is terminated by a balance impedance Z_{3b}, the Equal-Level Echo Path Loss from port 1 to port 2 is given by

$$ELEPL12 = -20 \log|s_{21B}| - (T - R), \tag{17}$$

where $-20 \log|s_{21B}|$ represents the voltage gain, in dB, from port 1 to port 2, T is the transmitted signal level at 1 kHz at port 1, and R is the received signal level at 1 kHz at port 2. We define

$$\delta_3 = \frac{Z_{3b} - Z_3}{Z_{3b} + Z_3} \tag{18}$$

$$\gamma_3 = \frac{Z_3 - Z_{03}}{Z_3 + Z_{03}} \tag{19}$$

$$\gamma_{3b} = \frac{Z_{3b} - Z_{03}}{Z_{3b} + Z_{03}}, \tag{20}$$

where Z_{03} is the primary reference impedance and Z_3 is the secondary reference impedance at port 3. It can be shown that

$$\gamma_{3b} = \frac{\gamma_3 + \delta_3}{1 + \gamma_3\delta_3}. \tag{21}$$

The reference impedances for the final model are $\{Z_{01}, Z_{02}, Z_{03}\}$, while the reference impedances for s_{21B} are $\{Z_{01}, Z_{02}, Z_{3b}\}$. The conversion technique for converting the scattering parameters under a change of reference impedances must be used.[6] The conversion factors are

$$\Gamma_1 = \Gamma_2 = 0 \quad \text{and} \quad \Gamma_3 = \gamma_{3b}, \tag{22}$$

and it can be shown that

$$s_{21B} = s_{21} + \frac{\gamma_{3b}s_{23}s_{31}}{1 - \gamma_{3b}s_{33}}$$

or

$$s_{21} = s_{21B} - \frac{\gamma_{3b}s_{23}s_{31}}{1 - \gamma_{3b}s_{33}}. \tag{23}$$

Thus, a 2-wire to 4-wire (or 4-wire to 2-wire) segment is represented by a 3 × 3 matrix, eq. (9), with its elements described in (10), (11), (14), (16), and (23).

A 4-wire to 4-wire segment (Fig. 6), in reality, can be considered as two unidirectional 2-port networks. A 2 × 2 matrix can be used to represent either the transmit or the receive path:

$$\{s_{ij}\} = \begin{bmatrix} s_{11} & 0 \\ s_{21} & s_{22} \end{bmatrix}, \tag{24}$$

where s_{ii} ($i = 1, 2$) is a function of return loss at port i,

$$s_{21} = g_{21}\sqrt{R_1/R_2}, \tag{25}$$

and g_{21} is the gain from port 1 to port 2.

3.6 Example

We will use the network services circuit shown in Fig. 3 as an example for the following studies:

1. Circuit (end-to-end) transducer loss of a 2-repeater circuit
2. Applications of generic equipment models to 2-wire network services circuit design
3. Sensitivity of transmission performance measures to return loss deviations.

It can be shown that for a 2-repeater/3-facility 2-wire network services circuit the transducer loss, L (in dB), is given as[7]

$$L = \sum_{i=1}^{3} L_i - \sum_{j=1}^{2} G_j + L_e + 10 \log \frac{R_{21}R_{22}}{R_{11}R_{12}}, \tag{26}$$

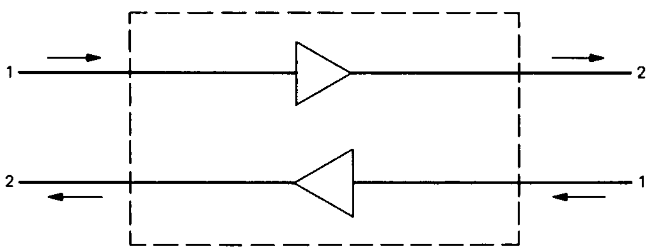


Fig. 6—A 4-wire to 4-wire generic segment.

where L_i is the transducer loss, in dB, of facility i; G_i is the voltage gain, in dB, of repeater j. Also

$$L_e = 20 \log|t_e| \tag{27a}$$

$$t_e \simeq 1 - \rho_{221}\rho_{112}s_{212}s_{122}, \tag{27b}$$

where ρ_{221} is the output reflection coefficient of repeater 1, ρ_{112} is the input reflection coefficient of repeater 2, s_{212} is the s_{21} of repeater 2, s_{122} is the s_{12} of repeater 2, and R_{1i} (R_{2i}) is the nominal input (output) resistance of repeater i.

In practical applications we have $R_{11} = R_{21}$ and $R_{12} = R_{22}$. Therefore eq. (26) becomes

$$L = \sum_{i=1}^{3} L_i - \sum_{j=1}^{2} G_j + L_e. \tag{28}$$

Thus, for a 2-repeater/3-facility 2-wire network services circuit, *the circuit transducer loss is equal to the sum of facility transducer losses minus the sum of repeater gains plus an error term, L_e.* In most applications, L_e has a value between 0 and 0.3 dB.

The models developed in this section have been applied to several cases. The 2-wire network services circuit shown in Fig. 3 has been analyzed. A chi-square random number generator was used to generate return losses meeting specified minimum and median requirements. (The rationalization for using chi-square distribution can be found in Ref. 10.) A Monte Carlo method was applied for the circuit simulation.[11] The Universal Cable Circuit Analysis Program (UNICCAP) was used to analyze the specific repeaters, used in the circuit.[12] The results were in complete agreement with the results obtained from generic equipment models.

The transducer loss or the attenuation distortion requirements of a network services circuit are specified by upper and lower templates for gain-frequency response of the circuit. Let $L(f)$ be the transducer loss at any frequency f. Then the attenuation distortion $D(f)$ is defined as

$$D(f) = L(f) - L(1 \text{ kHz}). \tag{29}$$

Figure 7a shows the upper template, D_u, the lower template, D_ℓ, and the median curve, D_m, for a typical attenuation distortion objective. For analytic purposes, these templates are smoothed as shown in Fig. 7b. Note that with a proper scale for the vertical axis in Fig. 7b, the templates specify the transducer loss instead of the attenuation distortion requirement of the circuit.

The results for the circuit shown in Fig. 3 are given in Fig. 8. It is clear from Fig. 8 that this 2-repeater/3-facility network services circuit provides a satisfactory performance.

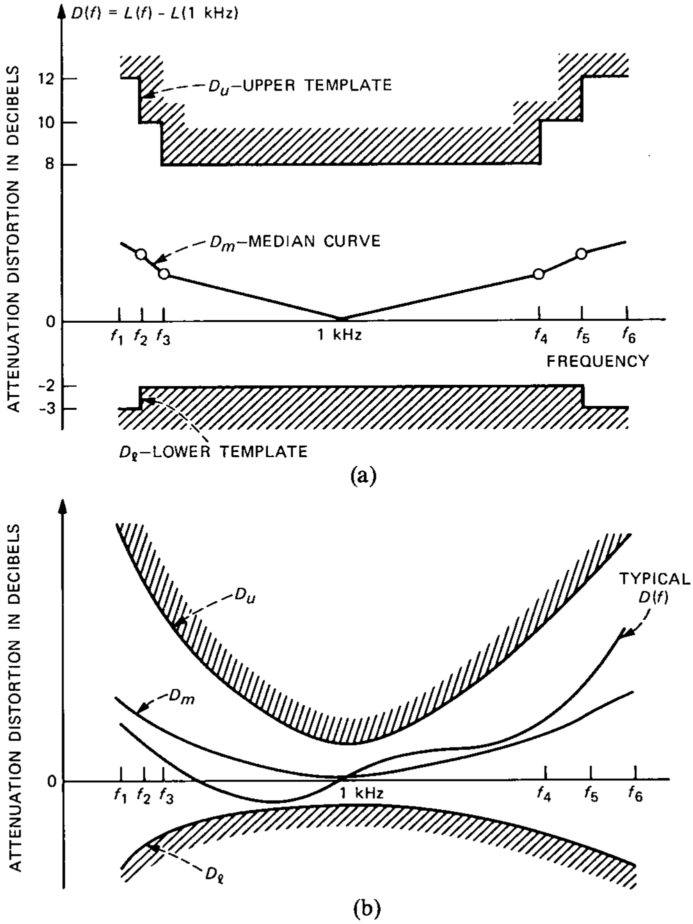


Fig. 7—Template and median curves for attenuation distortion objective: (a) Attenuation distortion objective; (b) smoothed attenuation distortion objective.

A sensitivity study of transmission performance was also made for this example. It was found that deviating all the return losses 6 dB from their nominal values would result in a circuit that would no longer provide satisfactory performance. Figure 9 shows the gain-frequency response in this case. This confirms with practical experience that return loss (or impedance mismatch) is a critical transmission performance measure.

The results obtained from this study indicate that the generic equipment models developed here are valid and useful. It is easy to apply them to assess a candidate design process in the generic design of network services circuits.

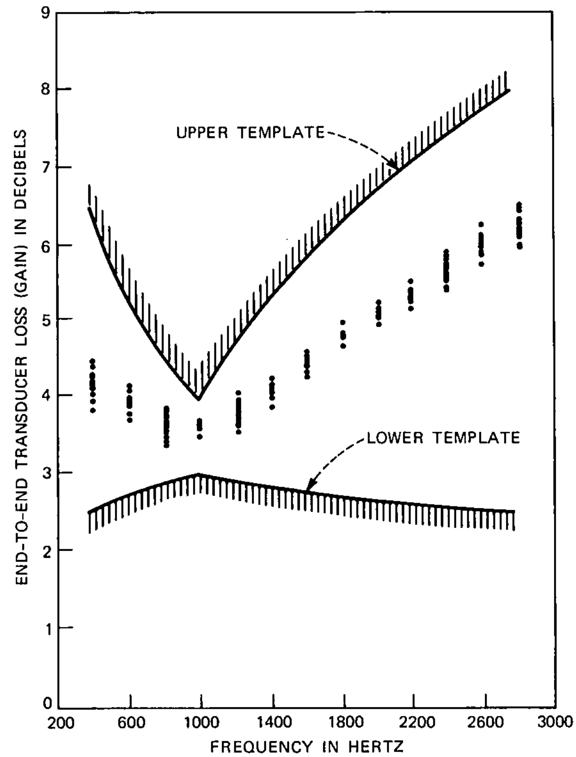


Fig. 8—Gain-frequency response with typical return-loss performance.

IV. THE ANALYSIS TOOL

Network services circuits are designed based on the *nominal* information about the transmission facilities and equipment. However, the parameters of the transmission facilities and equipment are subject to inevitable variations around their nominal values. These variations may be due to temperature changes, quantization, aging, etc. Statistical characterizations of these variations are often available from previous data. The design objective must be satisfied despite these variations.

The problems encountered here involve the determination of constraints on some parameters of the circuit while constraints on the remaining parameters of the circuit are specified. More specifically, let us assume that the design configuration, the design strategy, and the design objective are known. The associated problems can then be divided into the following three types:

1. Given the specifications of the transmission facilities, determine the type of equipment to be used. (Note that if generic equipment models are available for each design configuration, then the type of

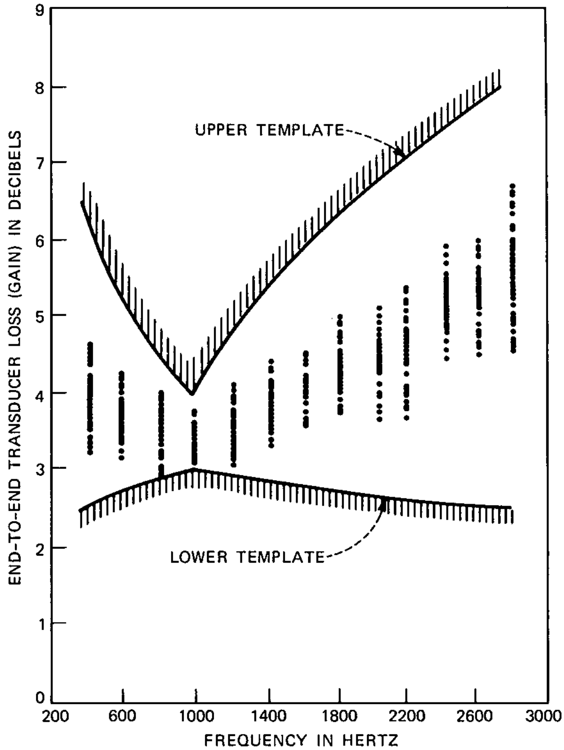


Fig. 9—Gain-frequency response with degraded return-loss performance.

equipment will refer to the constraints on the parameters of the models.)

2. Given the specifications of the equipment, determine the maximum application range of the facility sections.

3. Given partial specifications of the transmission facilities and equipment, determine the constraints on the remaining equipment parameters and the maximum range of the remaining facility sections.

Regardless of the type of problem, the analysis tool should be capable of determining the constraints on the unknown parameters of the circuit based on the available information about the specified parameters, such that the design objective is satisfied. In the following subsections we first discuss the nature of the objective functions in such problems. We then describe the analysis tool used to determine the optimal constraints. Finally, we illustrate the results by an example.

4.1 Nature of objective functions

Network services circuits must be designed such that circuit requirements on each overall performance measure are satisfied. Due to variations in the transmission facility and equipment parameters, circuit requirements cannot be fixed at exact deterministic values. (Such exact values are referred to as *target* or *design-center* values.) The circuit requirements are, of necessity, statistical in nature; that is, variations around design target values are specified statistically.

An example of a circuit requirement is that related to circuit transducer loss at 1 kHz, $L(1000)$, as described blow. If the target circuit transducer loss at 1 kHz is $\bar{L}(1000)$, then it may be specified that in PC_i percent of circuit samples, the transducer loss is not to deviate by more than Δ_i dB from the design target value ($i = 1, 2, \cdots$); that is, $|L(1000) - \bar{L}(1000)| \leq \Delta_i$. We define

$$NP_1 = |L(1000) - \bar{L}(1000)| \tag{30}$$

as a normalized circuit parameter and specify statistical bounds on NP_1. The collection of such statistical circuit requirements on the normalized circuit parameters is collectively referred to as the *design objective.* Figure 10 shows an element of the design objective for a typical special services circuit, i.e., a foreign exchange (FX) line. In this figure, which refers to circuit transducer loss, we have $NP_1 = |L(1000) - 3.5|$ and

$$NP_1 < 0.5 \text{ dB}, \quad PC_1 = 95; \quad NP_1 \leq 1.0 \text{ dB}, \quad PC_2 = 5. \tag{31}$$

Note that the design target value for NP_1 is zero. The cumulative

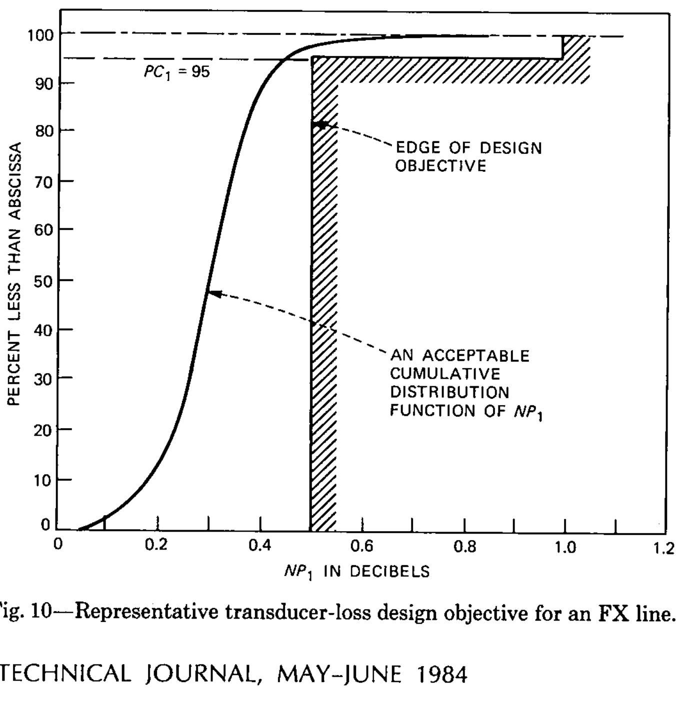


Fig. 10—Representative transducer-loss design objective for an FX line.

distribution of NP_1 for a large number of circuits designed by the application of a certain design strategy is referred to as the design performance. A typical design performance curve is also shown in Fig. 10. Note that any design performance curve that falls to the left of the "edge of the design objective" in Fig. 10 is acceptable.

Another example of a circuit requirement is that related to attenuation distortion. We define the normalized circuit parameter in this case as

$$NP_2 = \min_{400 \le f \le 2800} \psi(f), \tag{32}$$

where $\psi(f)$ is the *latent loss distortion* of the circuit, defined as follows:

$$\psi(f) = \begin{cases} \dfrac{D(f) - D_\ell}{D_m - D_\ell} & \text{for} \quad D_\ell \le D(f) \le D_m \\ \dfrac{D_u - D(f)}{D_u - D_m} & \text{for} \quad D_m \le D(f) \le D_u \\ D(f) - D_\ell & \text{for} \quad D(f) < D_\ell \\ D_u - D(f) & \text{for} \quad D(f) > D_u. \end{cases} \tag{33}$$

In the above equation, $D(f)$ is the difference between circuit transducer loss at frequency f and at 1000 Hz given in eq. (29), D_ℓ and D_u are the lower and upper bounds on the loss-versus-frequency characteristic of the circuit, and D_m is the median curve between D_ℓ and D_u. Figure 11 shows the upper and lower templates for gain-frequency response of a foreign exchange (FX) line where, for convenience, the curves D_ℓ and D_u are made piecewise linear. Figure 12 shows the statistical bounds on NP_2. In this figure we have

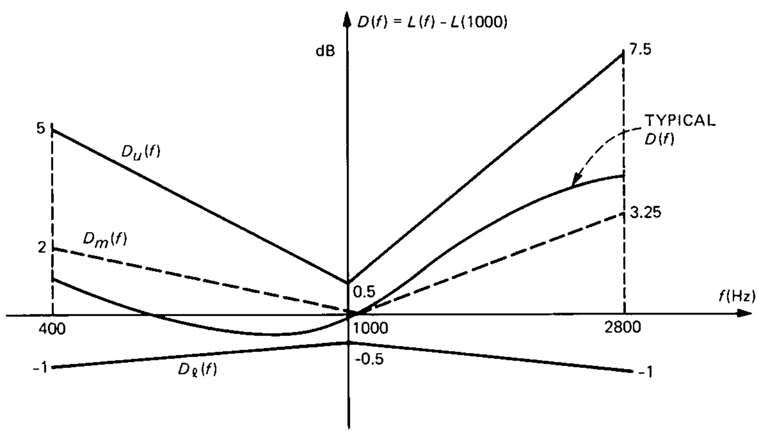


Fig. 11—Piecewise linear template and median curve for attentuation distortion design objective of an FX line.

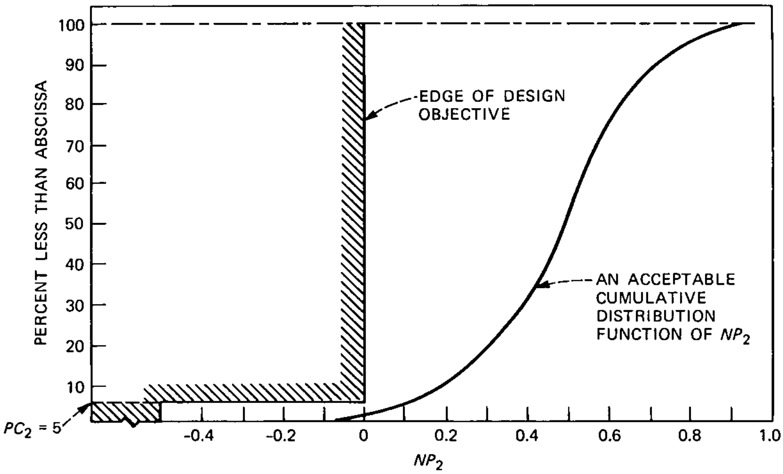


Fig. 12—Representative attenuation distortion design objective for an FX line.

$$NP_2 > -0.5, \qquad PC_1 = 5; \qquad NP_2 \geq 0, \qquad PC_2 = 95. \qquad (34)$$

Note that the target value for NP_2 (as well as the maximum value it can assume) is 1.

Equation (34) indicates that a 5-percent deviation from the design requirement related to attenuation distortion will be tolerated. Another way of interpreting this is that the design process will produce circuits that meet requirements in 95 percent of the time (assuming ergodicity).

4.2 Methods of optimization

The optimization problem under consideration can be stated as follows. Given the nominal values of and the statistical information about some parameters of the circuit, determine the constraints on the remaining parameters of the circuit such that the design objective is satisfied.

We use a Monte Carlo procedure[11] to simulate the circuit, i.e., to include the deviations from nominal parameter values, and to evaluate the design performance. To illustrate the procedure, consider a circuit including a set of unspecified parameters p_i, $i = 1, 2, \cdots, n$ (as well as a set of specified parameters) that are subject to variations. The circuit is assumed to meet the design target when parameters are at their nominal values. The value of each parameter can vary according to a certain statistical distribution within a range containing its nominal value. Parameter values may have upper bounds, lower bounds, or both upper and lower bounds. The problem is to determine bounds on the values of parameters p_i which result from meeting the design objective. The basic method to be used consists of the following three steps:

1. Determine the nominal parameter values $\bar{p}_i$, $i = 1, 2, \cdots, n$.
2. Choose suitable initial bounds for parameter values around their nominal values.
3. Analyze and evaluate the circuits resulting from the random choice of parameter values within their corresponding (initialized or specified) bounds.
4. Determine how these bounds should be modified to improve the design performance.

Steps 3 and 4 are repeated until the design objective is met. These steps involve statistical analysis of the results and their interpretation.

After determining the nominal values for the unspecified circuit parameters, one of the following three basic approaches can be employed:

1. Choose arbitrary initial bounds on parameter values and use iterations to tighten or loosen the bounds.
2. Choose sufficiently large initial bounds on parameter values and use iterations to tighten the bounds.
3. Choose sufficiently small initial bounds on parameter values and use iterations to loosen the bounds.

We use a combination of the first and second approaches. More specifically, we use the first approach to determine suitable initial bounds on parameter values. Note that the nominal values of parameters must fall within these initial bounds. The initial bounds on parameter values must be sufficiently loose so that no unnecessary constraint is placed on any parameter. At the same time, they should not be so loose as to cause the procedure not to converge in a reasonable number of iterations. We then gradually tighten these bounds, through iterations, until the design objective is met.

The flowchart of the above procedure is shown in Fig. 13. In this figure, the INITIALIZER is a software module which provides initial bounds on parameters p_i based on the properties of these parameters and the circuit. The Monte Carlo circuit analysis program in each pass uses samples of parameters p_i, generated by proper random number generators, and analyzes the resulting circuit to determine whether or not it meets the requirements. The CIRCUIT ANALYSIS MODULE in the flowchart of Fig. 13 is a software module which, for given design configuration, facility specifications, and equipment parameters, analyzes the circuit (e.g., by using the methods of Section III) and determines the normalized circuit parameters. The results of each pass through the algorithm are stored. The INTERPRETER in Fig. 13 is a software module that uses the stored results to determine

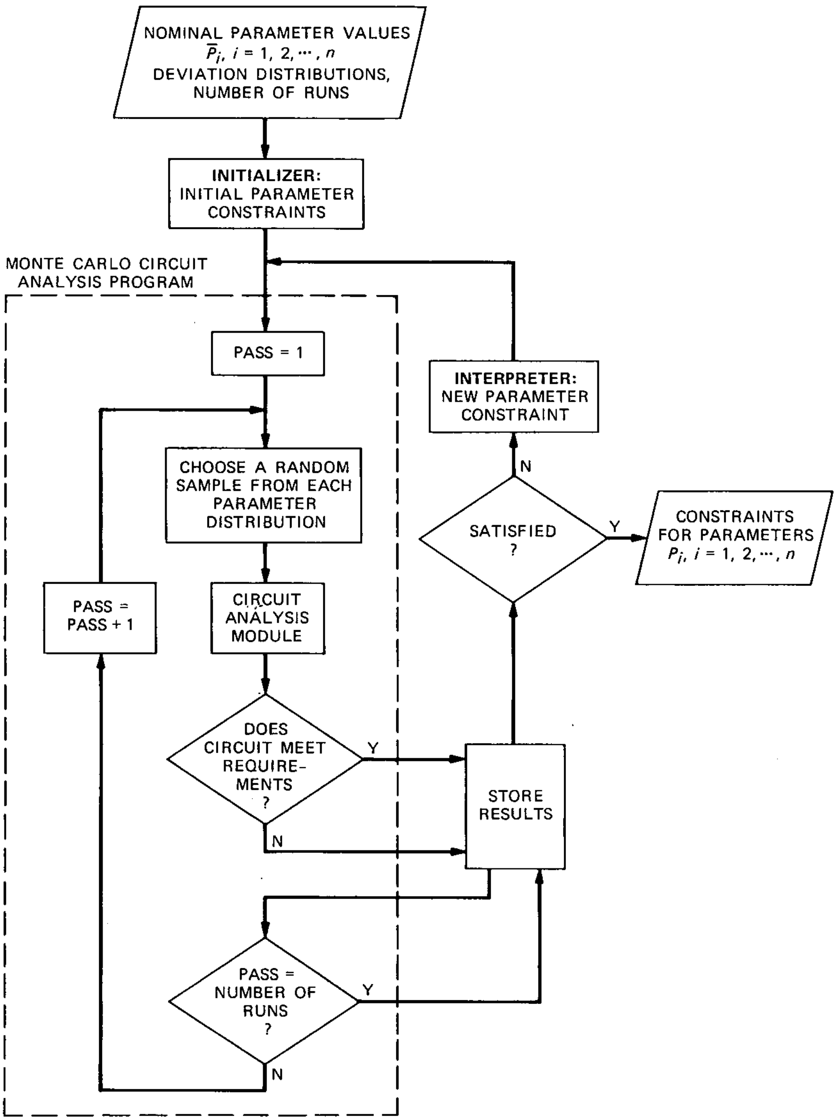


Fig. 13—Statistical analysis procedure.

the parameter whose bounds must be modified, as well as the new bounds for it such that a larger proportion of circuits will meet the requirements in the next Monte Carlo run. The algorithms used by the INTERPRETER are explained in Appendix B. The Monte Carlo runs are repeated until a set of bounds are produced for parameter values that meet the design objective.

4.3 The equipment requirements optimization process

One of the objectives of the generic design process is to facilitate the incorporation of general network equipment products into the circuit design process. To accomplish this, one has to determine the admissible ranges of values for equipment parameters used in various design configurations. In this section we will explain a computer-aided approach developed to determine the widest possible ranges for the values of equipment parameters in a given design configuration. More specifically, we assume that the design configuration and the facility specifications are known. We want to find maximum tolerances for the equipment parameters based on the given design strategy and design objective. Let us indicate the equipment parameters by p_{ij}; $i = 1, 2, \cdots, n_j$; $j = 1, 2, \cdots, N$, where n_j denotes the number of parameters related to equipment E_j, and N denotes the total number of equipment items in the circuit. The basic flowchart for the equipment requirements optimization process is shown in Fig. 14. The process consists of four steps:

1. Determine the nominal circuit solution.
2. Check the design strategy.
3. Initialize the process.
4. Analyze and interpret.

These procedures will be explained below.

4.3.1 Determine the nominal circuit solution

In this procedure the facility specifications are fixed at their nominal values. The design strategy is then applied to determine the nominal values of the equipment parameters, i.e., $\bar{p}_{ij}$, $i = 1, 2, \cdots, n_j$; $j = 1, 2, \cdots, N$. This corresponds to the initial setting of the equipment in the circuit.

4.3.2 Check the design strategy

This procedure determines whether the design strategy will lead to a satisfactory circuit when all the equipment parameters are fixed at their nominal values. Through a Monte Carlo procedure the circuit is subjected to variations in the lengths of facility sections, and the design performance (i.e., the cumulative distributions of various transmission performance measures) is determined. The block indicated as PERFORMANCE COMPARATOR in the flowchart of Fig. 14 compares the design performance P with the design objective Φ. If the design objective is met (indicated by $P \geq \Phi$), the process will continue to the initialization procedure. Otherwise, it is concluded that the design strategy is not suitable and the process will be aborted.

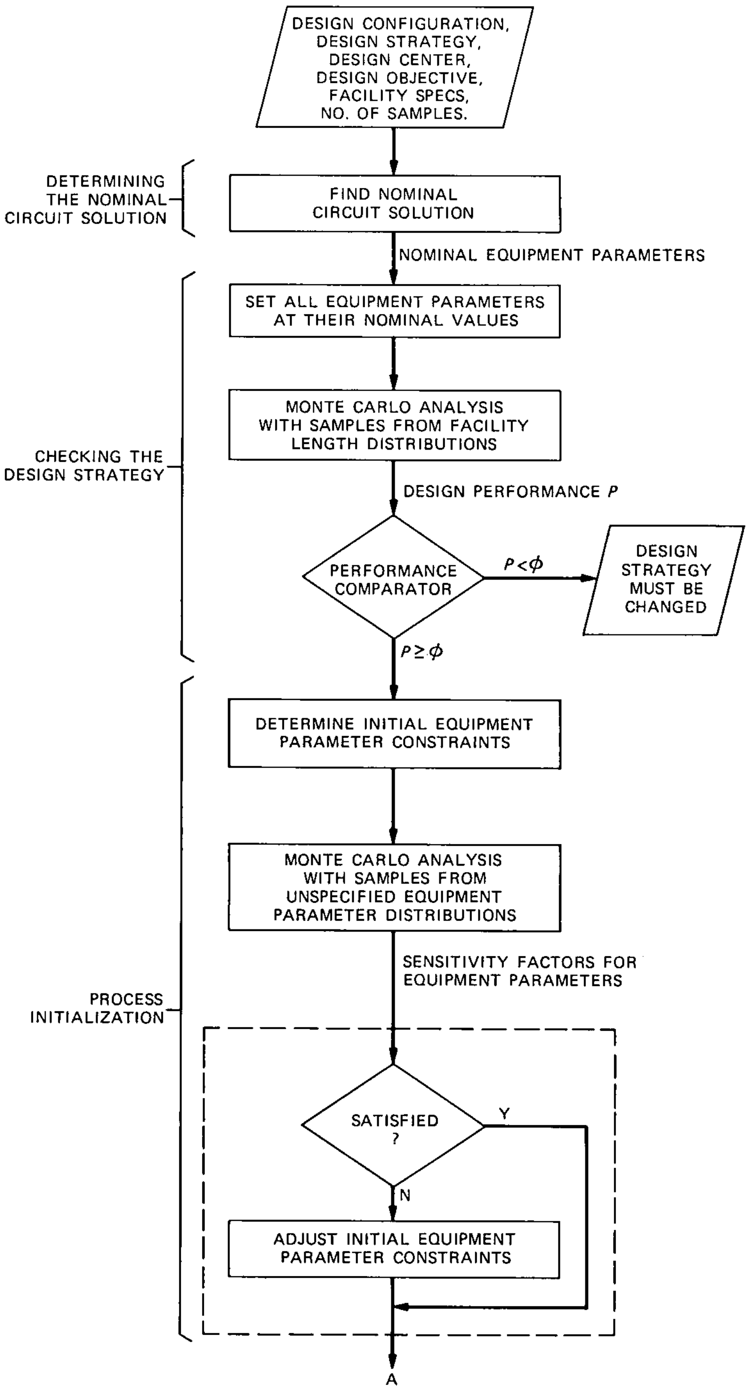
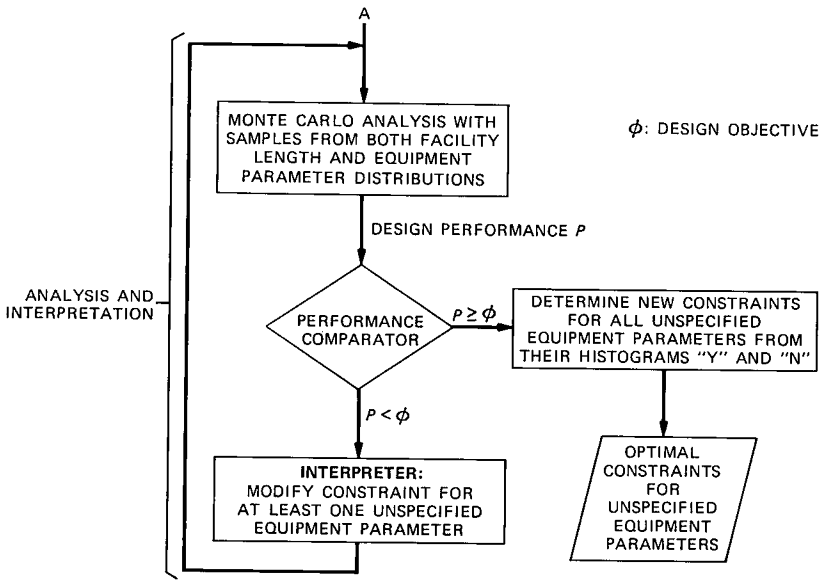


Fig. 14—Basic flowchart of the equipment requirement optimization process.



4.3.3 Initialize the process

The initialization procedure determines suitable initial constraints for equipment parameters. The method of choosing these initial constraints is as follows:

1. For one-sided equipment parameters with upper bounds, we let

$$p_{ij} = \bar{p}_{ij} + \delta_{ij}, \tag{35}$$

where random variable δ_{ij} represents variations around the nominal parameter value $\bar{p}_{ij}$. It is chosen from a uniform distribution whose mean and standard deviation are both equal to $x_{ij}\,|\,\bar{p}_{ij}\,|$, where x_{ij} is an input constant.

2. For one-sided equipment parameters with lower bounds, we let

$$p_{ij} = \bar{p}_{ij} - \delta_{ij}, \tag{36}$$

where the random variable δ_{ij} is chosen from a uniform distribution whose mean and standard deviation are as given above.

3. For two-sided equipment parameters, we use p_{ij} given by eq. (35), where the random variable δ_{ij} is chosen from a uniform distribution with zero mean, and the standard deviation $x_{ij}\,|\,\bar{p}_{ij}\,|$, where x_{ij} is an input constant. Initially all factors x_{ij} are chosen equal to x, which is an input to the process (e.g., $x = 0.1$).

To check the suitability of the initial constraints on equipment parameters based on the input value of x, a Monte Carlo analysis is performed in which samples are taken from the parameters of unspecified equipment just defined. Note that at this point facility lengths will be fixed at their nominal values. A bad choice for x may overconstrain some equipment parameters, or may cause the problem not to converge to a suitable solution in a reasonable number of runs. Decision on the suitability of the value of x is based on the values of the sensitivity factors M_{ij} of parameters p_{ij} as explained below. (See Appendix B for the definition of sensitivity factor.) We compare the sensitivity factors M_{ij} with two input values $M_{\min}$ and $M_{\max}$. (Typical values: $M_{\min} = 0.4$, $M_{\max} = 1.6$.)

1. If $M_{ij} < M_{\min}$, it is concluded that equipment parameter p_{ij} is undersensitive to variations; thus the initial range for this parameter must be loosened.

2. If $M_{ij} > M_{\max}$, it is concluded that p_{ij} is oversensitive to variations and the corresponding initial range must be tightened.

3. If $M_{\min} \leq M_{ij} \leq M_{\max}$, the initial range for p_{ij} will not be changed. Note that the initial range for equipment parameter p_{ij} is related to the value of x_{ij}. To adjust the initial range, new values for x_{ij} are determined according to the following algorithm, which has proved to work satisfactorily. For $i = 1, 2, \cdots, n_j$; $j = 1, 2, \cdots, N$; if $M_{ij} < M_{\min}$,

$$x_{ij}^{\text{new}} = (1 + M_{\min} - M_{ij})x_{ij}^{\text{old}}, \tag{37}$$

if $M_{ij} > M_{\max}$,

$$x_{ij}^{\text{new}} = (1 + M_{\max} - M_{ij})x_{ij}^{\text{old}}; \tag{38}$$

and if $M_{\min} \leq M_{ij} \leq M_{\max}$,

$$x_{ij}^{\text{new}} = x_{ij}^{\text{old}}. \tag{39}$$

4.3.4 Analyze and interpret

This part of the process involves iterations during which the initial equipment parameter ranges are tightened just enough to achieve satisfactory design performance. The procedure is based on a Monte Carlo analysis where samples are chosen from both facility length and equipment parameter distributions. After each Monte Carlo run, the block indicated as PERFORMANCE COMPARATOR in the flowchart of Fig. 14 compares the design performance P with the design objective Φ. If the design objective is not met, the constraint for at least one parameter will be modified (as will be explained) and the Monte Carlo analysis procedure is repeated. The Monte Carlo runs continue until the design objective is met, at which point the final constraints for equipment parameters are determined.

The procedure for the modification of constraints for equipment parameters is based on the algorithms described in Appendix B. This procedure is as follows. Let

$$\max_{i,j} M_{ij} = M_{IJ}, \tag{40}$$

where M_{IJ} is the sensitivity factor corresponding to equipment parameter p_{IJ}. Consider the following cases:

1. p_{ij} is one-sided with an upper limit. In this case the intersection of "Y" and "N" histograms for p_{ij} will be the new upper limit (see Fig. 15a).

2. p_{ij} is one-sided with a lower limit. In this case the intersection of "Y" and "N" histograms for p_{ij} will be the new lower limit (see Fig. 15b).

3. p_{ij} is two-sided. In this case the intersection of "Y" and "N" histograms for p_{ij} defines the new range for this parameter as shown in Figs. 15c and 15d. (If "Y" histogram is on the right side of "N" histogram, the new range will be determined from the "Y" histogram, as shown in Fig. 15c.)

4.3.5 Incremental analysis

It is desirable to let the nominal characteristics (e.g., loss) of each facility section vary within a range. In such a case we would like to determine the corresponding ranges for the nominal values of equipment parameters. Also, it will still be desirable to determine the loosest possible constraints on equipment parameters for each set of nominal facility specifications. An example (Section 4.4) will demonstrate that the *nominal* values of equipment parameters depend only on the *nominal* facility specifications, and that the optimal *variations* around the nominal values of equipment parameters depend only on the *variations* around nominal facility specifications.

4.4 Example

This section demonstrates the equipment requirements optimization process on a foreign exchange (FX) line. The circuit under consideration consists of three 2-wire metallic facility sections and two repeaters, as shown in Fig. 3. In general, metallic facility sections can be specified by their physical parameters such as length, gauge, and loading characteristics. Using the Universal Cable Circuit Analysis Program (UNICCAP),[12] the loss for each facility section can then be calculated for standard terminations at any frequency. We assume, for convenience, that the facility sections in Fig. 3 are specified via their respective nominal losses at frequencies of 400, 1000, and 2800 Hz. Further, we assume that the loss at frequency f of each facility section F_i is subject to variation $\Delta_i(f)$. Thus, the losses for the facility sections are given by

$$L_i(f) = \bar{L}_i(f) + \Delta_i(f), \qquad i = 1, 2, 3$$
$$f = 400, 1000, 2800 \text{ Hz}, \tag{41}$$

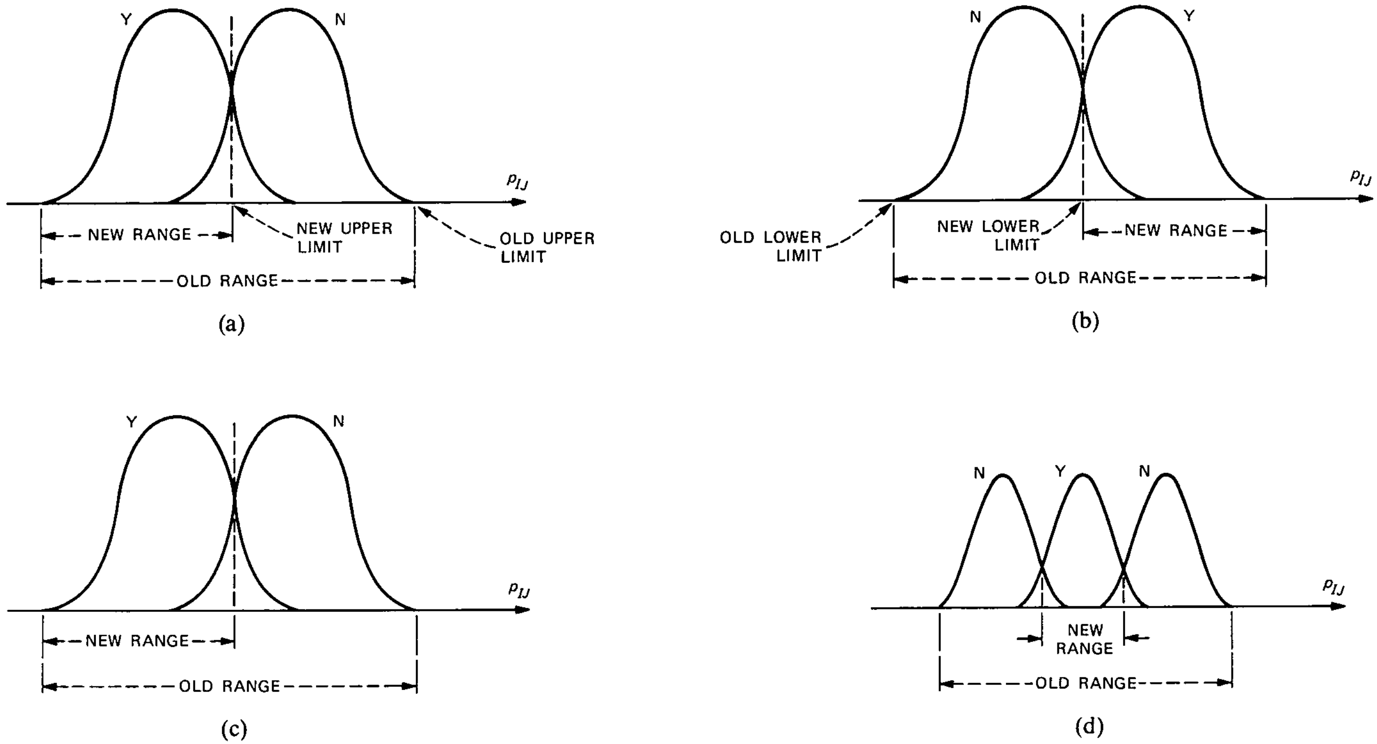


Fig. 15—Typical "Y" and "N" histograms for equipment parameter p_{IJ}. (a) One-sided parameter with upper limit. (b) One-sided parameter with lower limit. (c), (d) Two-sided parameter.

where $\bar{L}_i(f)$ indicates the nominal loss of facility section F_i at frequency f and $\Delta_i(f)$ is a random variable indicating variations around $\bar{L}_i(f)$. The type of distribution for $\Delta_i(f)$ can be specified as well. Here we assume that $\Delta_i(f)$, $i = 1, 2, 3$ are normally distributed with zero means and with specified standard deviations. We indicate the lower and the upper limits of nominal loss of facility F_i by $\bar{L}_{li}$ and $\bar{L}_{ui}$, respectively. These values as well as the values of $\Delta_i(f)$ for the example under consideration are given in Table II.

The equipment parameters used in this example are the gains of the repeaters at frequencies 400, 1000, and 2800 Hz, i.e.,

$$p_{11} = G_1(400), \quad p_{21} = G_1(1000), \quad p_{31} = G_1(2800)$$
$$p_{12} = G_2(400), \quad p_{22} = G_2(1000), \quad p_{32} = G_2(2800), \tag{42}$$

where $G_j(f)$ indicates the gain of repeater E_j at frequency f. The above parameters are all two-sided, i.e., an upper bound and a lower bound must be determined for each. Similar to eq. (41), we can write

$$G_j(f) = \bar{G}_j(f) + \delta_j(f), \qquad j = 1, 2$$
$$f = 400, 1000, 2800 \text{ Hz}. \tag{43}$$

We are looking for the values $\bar{G}_j(f)$ as well as the characteristics of random variables $\delta_j(f)$.

The normalized circuit parameters NP_1 and NP_2 and the design objective defined in eqs. (31) to (33) and depicted in Figs. 10 and 12 will be used in this example. Using eqs. (28), (41), and (43), we can easily show that

$$NP_1 = \left| \sum_{i=1}^{3} \Delta_i(1000) - \sum_{j=1}^{2} \delta_j(1000) \right|. \tag{44}$$

Table II—Facility specifications

Facility Section	Nominal Loss and Std. Dev. (in dB)	At 400 Hz	At 1000 Hz	At 2800 Hz
1	$\bar{L}_{l1}(f)$	3	5	9
	$\bar{L}_{ul}(f)$	5	7	11
	$\Delta_1(f)$	0.2	0.1	0.3
2	$\bar{L}_{l2}(f)$	7	9	11
	$\bar{L}_{u2}(f)$	9	11	13
	$\Delta_2(f)$	0.1	0.05	0.2
3	$\bar{L}_{l3}(f)$	4	7	11
	$\bar{L}_{u3}(f)$	6	9	13
	$\Delta_3(f)$	0.2	0.1	0.3

Notes: $L_i(f) = \bar{L}_i(f) + \Delta_i(f)$ and $\bar{L}_{li}(f) \le \bar{L}_i(f) \le \bar{L}_{ui}(f)$, $i = 1, 2, 3$; $f = 400, 1000, 2800$ Hz.

Also,

$$D(400) = D_m(400) + \sum_{i=1}^{3} \{\Delta_i(400) - \Delta_i(1000)\} - \sum_{j=1}^{2} \{\delta_j(400) - \delta_j(1000)\}, \tag{45}$$

$$D(1000) = 0, \tag{46}$$

and

$$D(2800) = D_m(2800) + \sum_{i=1}^{3} [\Delta_i(2800) - \Delta_i(1000)] - \sum_{j=1}^{2} [\delta_j(2800) - \delta_j(1000)], \tag{47}$$

where D_m is defined in Fig. 11, and $\Delta_i(f)$ and $\delta_j(f)$ are defined in eqs. (41) and (43), respectively. Thus the latent loss distortion $\psi(f)$ in eq. (32) can be calculated for f = 400, 1000, and 2800 Hz, and the normalized circuit parameter NP_2 in eq. (32) can be expressed in terms of $\Delta_i(f)$ and $\delta_j(f)$.

Design strategy refers to the transmission plan which, for specified facility sections, determines the nominal values of equipment parameters (i.e., the values of equipment parameters when all circuit parameters are at design-target values and facility sections are not subjected to deviations). The transducer loss of the circuit of Fig. 3 at frequency f can be calculated as follows:

$$L(f) \approx L_1(f) + L_2(f) + L_3(f) - G_1(f) - G_2(f), \tag{48}$$

where $L_i(f)$ indicates the loss of facility section F_i at frequency f Hz. Equation (48) is the same as eq. (28) where the error term L_e has been neglected for convenience. The above formula holds, of course, also for nominal values:

$$\bar{L}(f) \approx \bar{L}_1(f) + \bar{L}_2(f) + \bar{L}_3(f) - \bar{G}_1(f) - \bar{G}_2(f). \tag{49}$$

A typical design strategy for the example under consideration is as follows. For the gain adjustment aspect of the strategy, we use the following formulas:[13]

$$\bar{G}_1(1000) = \bar{L}_1(1000) + \frac{\bar{L}_2(1000)}{2} - \frac{3.5}{2} \tag{50}$$

$$\bar{G}_2(1000) = \bar{L}_3(1000) + \frac{\bar{L}_2(1000)}{2} - \frac{3.5}{2}, \tag{51}$$

where 3.5 dB is the design-target value for the 1-kHz circuit transducer loss. Solution of eqs. (50) and (51) results in the nominal values of repeater gains at 1 kHz. For the equalization aspect of the design strategy we use the following formulas [which are similar to eqs. (50) and (51)]:

$$\bar{G}_1(f) - \bar{G}_1(1000) = \bar{D}_1(f) + \frac{\bar{D}_2(f)}{2} - \frac{D_m(f)}{2} \tag{52}$$

$$\bar{G}_2(f) - \bar{G}_2(1000) = \bar{D}_3(f) + \frac{\bar{D}_2(f)}{2} - \frac{D_m(f)}{2} \tag{53}$$

for $f = 400$ and 2800 Hz, where

$$\bar{D}_i(f) = \bar{L}_i(f) - \bar{L}_i(1 \text{ kHz}) \tag{54}$$

represents the attenuation distortion corresponding to facility section F_i [cf. eq. (29)] and $D_m(f)$ is defined in Fig. 11. Solution of eqs. (52) and (53) results in the nominal values of repeater gains at frequencies 400 and 2800 Hz. Thus the implementation of the design strategy described above results in the nominal values of the six equipment parameters, i.e., $\bar{G}_j(f)$, $j = 1, 2$, $f = 400, 1000, 2800$ Hz based on the specified nominal values $\bar{L}_i(f)$ for facility sections. If the nominal values $\bar{L}_i(f)$ are allowed to vary in the range $[\bar{L}_{li}(f), \bar{L}_{ui}(f)]$, then the corresponding ranges $[\bar{G}_{lj}(f), \bar{G}_{uj}(f)]$ for each repeater nominal gain, $\bar{G}_j(f)$, must be found. To do this, we allow the nominal values $\bar{L}_i(f)$ to vary randomly within their specified ranges $[\bar{L}_{li}(f), \bar{L}_{ui}(f)]$ according to their specified (or assumed distributions). For each set of nominal facility losses, we determine the corresponding nominal repeater gains. Then the lower bounds and the upper bounds of nominal repeater gains will be determined.

A FORTRAN program, named EROP, was written for this example. Table III shows the corresponding output for the input specified in Table II. The number of iterations to achieve the final solution was 15.

Table III—EROP output for example in Section 4.4

Repeater	Nominal Gain (in dB)	At 400 Hz	At 1000 Hz	At 2800 Hz
1	$\bar{G}_{l1}(f)$	3.750	7.881	11.469
	$\bar{G}_{u1}(f)$	6.692	10.701	13.939
2	$\bar{G}_{l2}(f)$	4.752	10.033	13.226
	$\bar{G}_{u2}(f)$	7.616	12.574	15.939

Deviations of repeater gains (in dB):

$-0.2 \le \delta_1(400) \le 2.0$, $-0.2 \le \delta_1(1000) \le 0.4$, $-2.8 \le \delta_1(2800) \le 1.6$
$-1.6 \le \delta_2(400) \le 0.2$, $-0.2 \le \delta_2(1000) \le 0.2$, $-1.2 \le \delta_2(2800) \le 2.8$

Note: $G_j(f) = \bar{G}_j(f) + \delta_j(f)$ and $\bar{G}_{lj}(f) \le \bar{G}_j(f) \le \bar{G}_{uj}(f)$, $j = 1, 2$; $f = 400, 1000, 2800$.

V. CONCLUSION

A perspective on the design of network services circuits has been discussed and recent developments in modeling and analysis tools have been reported. Models that have been addressed cover voiceband network equipment and are parameterized on a functional basis in terms of commonly used transmission measures. Tests show the models are consistent with the behavior of network equipment products. The optimization problem has been studied under general scenarios of fixed facility specifications, fixed equipment specifications, and partial specifications of facilities and equipment. Corresponding optimization methods have been developed and implemented in mechanized analysis tools to provide a viable procedure for determining needed standards on network equipment. These developments are providing much of the foundation needed for a generic approach to the design of network services circuits. Although the discussion has centered around voiceband cables and repeaters, the optimization techniques reported here can also be used in digital applications.

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APPENDIX A

Glossary

This appendix describes the terminology used in the main text of the paper. The terms are arranged in alphabetical order.

Circuit—The telecommunications transmission path providing the network services extending from one end (customer location or central office) to another.

Circuit parameters—Parameters that are important measures of circuit transmission characteristics (e.g., circuit transducer loss).

Design architecture—A circuit topology consisting of generic transmission facilities and equipment.

Design center (or design target)—Deterministic values that are specified targets for circuit parameters.

Design configuration—A circuit topology consisting of physical equipment and transmission facilities.

Design objective—Specified bounds on the statistical distributions of normalized circuit parameters.

Design performance—Statistical distributions of normalized circuit parameters.

Design strategy—A transmission plan that determines the nominal values of equipment parameters.

Equipment functional specifications—Constraints for values of equipment parameters with their corresponding distributions within the constraints.

Equipment parameters—A set of quantities whose values determine the characteristics of the equipment.

Facility configuration—A circuit configuration that represents a physical combination of transmission facilities without specifying the junction points between facilities.

Facility section—A portion of a circuit consisting of a transmission facility between two pieces of equipment.

Facility specifications—The type and the physical specifications of each facility section in the circuit, or equivalently, the transmission parameters of each facility section that are relevant to the measurement of circuit transmission characteristics.

Generic equipment model—A model whose primary parametric characterization is functional (e.g., transducer and return losses) rather than physical (e.g., resistance, inductance, and capacitance).

Generic segment—A circuit segment that is functionally characterized apart from any specific equipment technology.

Generic segment measures—The causes whose effects are the transmission performance measures.

Incremental analysis—Circuit analysis where only variations of parameters around their nominal values are considered.

Nominal circuit solution—The collection of nominal equipment parameters.

Nominal equipment parameters—The values of equipment parameters determined on the basis of the given facility specifications (with no deviations) and transmission plan such that all the circuit parameters are at design-center values.

Normalized circuit parameters—Parameters used to measure circuit performance. These parameters are derived from circuit parameters.

One-sided equipment parameters—Equipment parameters that are constrained either from above or from below.

Transmission performance measures—Measures that can characterize the transmission performance of a circuit.

Two-sided equipment parameters—Equipment parameters that are constrained both from above and from below.

APPENDIX B

The 'Interpreter' in the Statistical Optimization Program

B.1 Algorithm for modification of parameter ranges

For each random sample of parameters p_i, $i = 1, 2, \cdots, n$, we determine whether or not the resulting circuit meets the worst-case requirements defined by the design objective. Therefore, at the end of each Monte Carlo run we have two histograms (or probability density functions) of the values of each unspecified parameter corresponding to the circuits that meet or do not meet such requirements. We indicate these histograms by "Y" and "N" as shown in Fig. 16. From these histograms we will determine the ranges of values for parameters p_i over which the proportion of circuits meeting such requirements predominate.

Figure 16 illustrates the case where parameter p_i was assigned values in the original range, i.e., $\underset{\sim}{a} < p_i < \underset{\sim}{c}$, and the circuits with low values of p_i generally met the requirements. A new range for p_i is determined from the intersections of "Y" and "N" histograms as shown in Fig. 16. By restricting the values of parameter p_i to the new range (i.e., $\underset{\sim}{a} < p_i < \underset{\sim}{b}$) while the ranges of other parameters are unchanged, an increase will be expected in the proportion of circuits meeting the requirements in the next Monte Carlo run. This can be proved by the application of Bayes' Theorem of Statistics,[14] which relates a posteriori probability of events A_k subject to the occurrences of event B, $P_B(A_k)$, to a priori probabilities $P(A_j)$:

$$P_b(A_k) = \frac{P_{A_k}(B)P(A_k)}{P(B)} = \frac{P_{A_k}(B)P(A_k)}{\sum\limits_{j=1}^{n} P_{A_j}(B)P(A_j)}. \tag{55}$$

In eq. (55), events A_j, $j = 1, 2, \cdots, n$ are mutually exclusive and their union equals the universal event, and event B is arbitrary. Now consider the events

$$\begin{aligned} &A_1 = Y\text{: circuit meets requirements} \\ &A_2 = N\text{: circuit does not meet requirements} \\ &B\text{: } a < p_i < b. \end{aligned} \tag{56}$$

Note that

$$P(N) = 1 - P(Y). \tag{57}$$

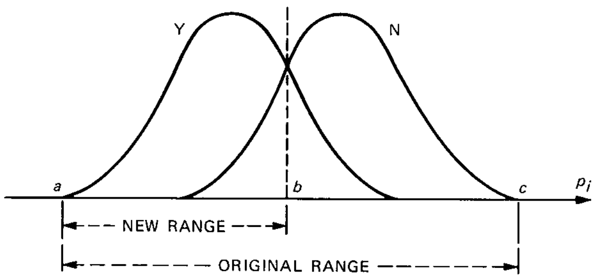

Fig. 16—Histograms of parameter p_i corresponding to circuits that meet the requirements "Y" or do not meet the requirements "N".

Thus, for $k = 1$ and $n = 2$, eq. (55) becomes

$$\underset{a < p_i < b}{P(Y)} = \frac{P_Y(p_i < b)P(Y)}{P_Y(a < p_i < b)P(Y) + P_N(a < p_i < b)P(N)}. \tag{58}$$

We want to show that the above algorithm for range modification at the end of each Monte Carlo run leads to an improvement on the probability of circuits meeting the requirements. That is, we want to prove that

$$\underset{a<p_i<b}{P(Y)} > P(Y). \tag{59}$$

Histograms "Y" and "N" in Fig. 16 represent conditional probability densities $P_Y(p_i)$ and $P_N(p_i)$ for parameter (random variable) p_i in circuits meeting or not meeting the requirements, respectively. We have, from Fig. 16,

$$P_Y(p_i) > P_N(p_i) \quad \text{for} \quad a < p_i < b. \tag{60}$$

Thus,

$$\begin{aligned} P_Y(a < p_i < b) = \int_a^b P_Y(p_i)dp_i > \int_a^b P_N(p_i)dp_i \\ P_N(a < p_j < b). \end{aligned} \tag{61}$$

Using eqs. (57) and (61) in eq. (58) and noting that $0 < P(Y) < 1$ yields eq. (59).

B.2 Algorithm for choosing the parameter for treatment

At the end of each Monte Carlo run we must determine the parameter whose range of values most influences the proportion of circuits meeting the requirements. This can be accomplished by a sensitivity factor M_i for each parameter p_i as follows:[15]

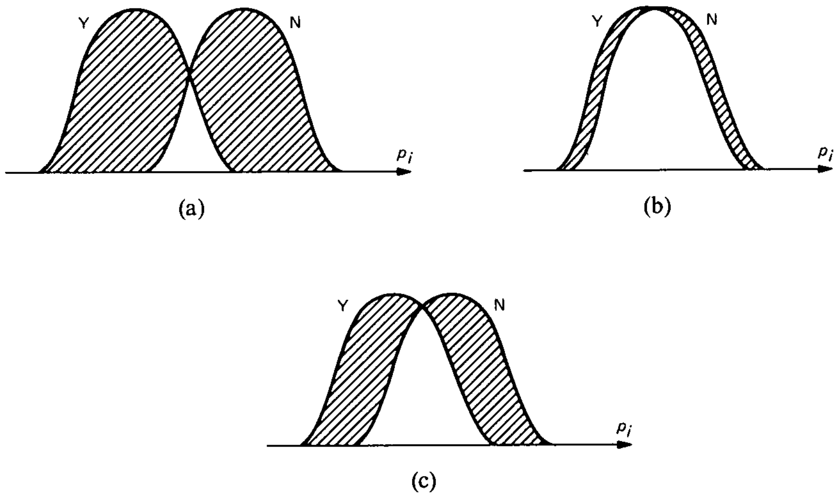

Fig. 17—Sensitivity factor M_i for parameter p_i. (a) $M_i \approx 2$. (b) $M_i \approx 0$. (c) $0 < M_i < 2$.

$$M_i = \int_{-\infty}^{+\infty} [P_Y(p_i) - P_N(p_i)]dp_i. \tag{62}$$

Sensitivity factor M_i is a measure of overlap of the probability density functions $P_Y(p_i)$ and $P_N(p_i)$. In fact, it is the area of the nonoverlapping parts of these density functions. It varies between zero for the case of complete overlap and two for the case of no overlap.

Figure 17 shows three different cases of overlap. Figure 17a corresponds to the case where circuits with sufficiently low values of p_i meet the requirements independent of variations in any of the other parameters. That is, in this case, parameter p_i is the determining factor in whether or not the circuit meets the requirements.

Figure 17b corresponds to the situation where the value of parameter p_i has no significant effect on whether or not the circuit meets the requirements. That is, the determining factor must be sought among other parameters. The case shown in Figure 17c is between the above two extreme situations.

At the end of each Monte Carlo run, the parameter with the largest sensitivity factor will be chosen for range modification, while keeping the ranges of values for other parameters unchanged.

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