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Statistical Circuit Design:

A Case Study of the Use of Computer Aids in Circuit Design—Pulse Equalizers for the T2 Digital Transmission Line

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Computer simulation makes it economically feasible to analyze competing circuit configurations and optimize the circuit parameters using complicated criteria related to system performance. Furthermore, the influence of manufacturing tolerances on optimized performance can be statistically investigated to establish component specifications before production is started. Thus, the designer can predict more easily whether or not a circuit will perform adequately in the field.

In addition, computer operated test sets can provide accurate measurements of circuit performance during manufacture to insure that the product will be satisfactory. These test facilities can be programmed to provide a factory evaluation of the individual circuits based on worst-case system performance.

To illustrate these concepts, it is shown how computer aids were utilized in the design of the pulse equalizers for the T2 digital transmission line. The discussion of the equalizer design is intended to illustrate why and in what manner the various functions were implemented. The statistical tolerance analysis and manufacturing test phases receive the greatest emphasis as they are the most recent developments.

I. INTRODUCTION

Tolerance analysis is the most recent development in a continuing effort to design circuits and systems realistically. Realism requires that you model as closely as possible the complex environment in which the requisite functions must be accomplished. As computers evolved, it has become economically feasible to take more and more factors into account. The objective of this effort is to anticipate potential problems so that they may be eliminated in the design phase rather than unexpectedly to discover them when the unit is put into service. Standard design practice is to progress through several test phases, first using breadboards and prototypes of individual circuits, then using complete systems in the field trials and limited service trials. If computer simulation is also employed during the design process, it is frequently possible to detect design deficiencies at an earlier stage, and the earlier the problem is detected the less expensive is the corrective action.

The impact that the computer has had on this quest for realism is most readily illustrated with a specific example. The design of the pulse equalizers for the T2 digital transmission line evolved during the era discussed in the introduction to this issue. Thus the improvements in computers and computer-aided design techniques made it possible to introduce more and more realism into the design process. Initially, the computer was used for analysis (by simulation) of the equalizer and the evaluation of complicated performance measures so that the engineer could make design decisions. Subsequently, when more powerful computers became available, the function of the computer was increased to provide automatic optimization of the circuit parameters. Next, the influence of manufacturing tolerances on optimized performance was statistically investigated to establish component specifications. When the prototypes were constructed, detailed measurements made on a Computer Operated Transmission Measurement Set (COTMS) were used to insure that the equalizers performed as predicted. Finally, the equalizers were tested at WECo on COTMS using a criterion that was representative of the one used in the design phase. This insured that the manufactured units would also provide the predicted performance.

The subsequent discussion is intended to illustrate why and how the various operations are implemented in order to obtain realistic predictions of performance. Since this is not intended as a history of the project, only those developments directly related to computer simulation are discussed. Although it is a specific example, the discussion can serve as a guide so that designers of other systems can profit from the experience gained with T2.

II. ANALYSIS AND OPTIMIZATION

2.1 *Design Requirements*

A set of pulse equalizers was designed for the T2 digital transmission line which operates at 6.3 million bits per second.[1,2] The equalizer is a basic part of the repeater shown in Fig. 1. Its function is to reshape the pulses dispersed by the cable into a shape suitable for deciding what level was transmitted. These pulses are then sampled and regenerated for retransmission. The input and output of a typical equalizer are shown in Fig. 2. The upper trace is an individual pulse after dispersion by the cable as received at point A in Fig. 1 and the lower is the same pulse at the output of the equalizer, point B.

An actual transmission consists of a sequence of these pulses spaced one signaling interval apart. Since this interval corresponds to one division in Fig. 2, it is evident that equalized as well as unequalized pulses would overlap. Even if the equalizer output pulse was sampled exactly at its peak, the typical pulse has nonzero values at adjacent sampling times separated by the signaling interval. These nonzero values interfere with the decision made at the neighboring sampling times; this is referred to as intersymbol interference. Thus, the equalizer design will be influenced both by variations in sampling time and intersymbol interference caused by adjacent pulses.

The performance measure for equalizer design should reflect the influence of as many factors as it is feasible to include that might affect the correct regeneration of the transmitted information. Thus, the design criterion was error rate, the rate at which errors are made in regeneration. Since, for example, the design requirement for each regenerator may be less than one error in 10^7 transmitted pulses, excessive computer time is required for accurate estimation by accumulating errors; instead, the probability of occurrence is calculated. This calculation includes most sources of interference, for example, intersymbol interference, sampling jitter, thermal noise, and crosstalk due to neighboring transmission paths. The probability of errors

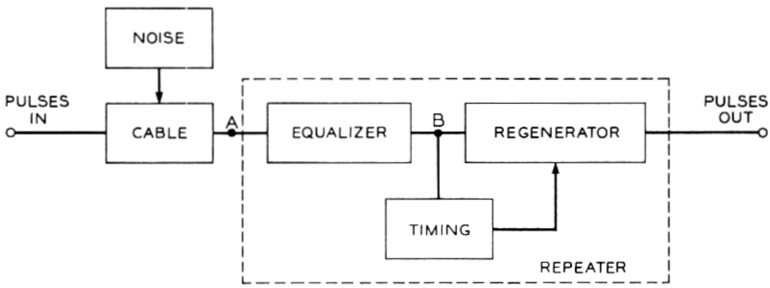

Fig. 1—A pulse repeater and its environment.

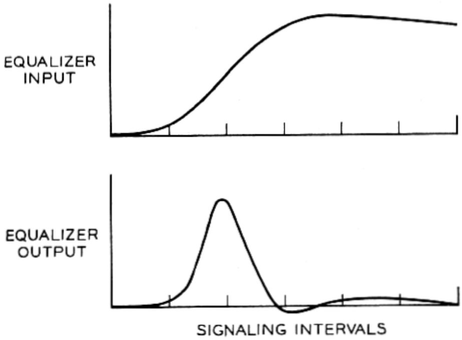

Fig. 2—Pulse interference caused by cable dispersion may not be entirely removed by equalization.

caused by noise can be kept low by maximizing the worst-case separation between adjacent signal levels; this separation is referred to as the eye opening.[1] The error rate will be a minimum if the eye opening which is inversely proportional to intersymbol interference is sampled at its largest point. It is the need to include all these factors in the criterion that makes it necessary to use a computer to obtain a realistic prediction of performance.

2.2 *Characterization of Transmission Medium*

In T2, the transmission medium is a twisted pair of insulated wires within a multi-pair cable. The dispersion produced by a cable pair depends on physical properties such as wire gauge, conductivity of the wire, capacitance, dielectric material and length of cable between regenerators; some of which are affected by temperature. To design an equalizer that compensates for dispersion, it is necessary that the medium be correctly modeled. This characterization requires that many individual cable pairs be accurately measured so that an average representation can be chosen that will reflect the proper dispersion of the pulses as cable length and temperature are varied. The averaging operation also smooths the data, thus minimizing the effect of measurement errors. Polynominals are then fitted to both the average loss and phase characterization. Thus, any required cable can be simulated by a proper choice of coefficients for the polynominals.

2.3 *Equalizer Configuration*

An adaptive configuration for the equalizer was selected to reduce the number of designs needed to cover the entire loss range, that is, allowable cable lengths. The basic configuration contains up to three constant-R shaping networks and an automatic line build out (ALBO) network. A bridged-T, constant-R section, as shown in Fig. 3, produces a real zero and a pair of complex poles in the transmission path for reshaping the dispersed pulses. The ALBO is two simple RL sections whose singularities are adjusted to keep the output amplitude and shape constant. The variable elements in the ALBO are resistances whose values are determined by the forward resistance of diodes in a feedback control loop. This brief description is adequate for the present; for additional details see Ref. 2.

To summarize, the analysis objective was to simulate how the equalizers respond to various cable lengths, temperatures, and input pulse shapes so that the probability of error could be calculated. This analysis followed two paths, a digital simulation for calculating the error rate of a specific equalized transmission channel, and an analog simulation for investigating the influence of equalizer parameters on pulse shape. These two approaches were combined in a hybrid simulation that was used for iterative optimization.

2.4 *Pulse Transmission Program (PTP)*

This digital program can be used for calculating the pulse shape, eye opening, and error rate of a particular equalizer attached to a specified cable. The representation of the equalizer may consist of models, experimental measurements, or a combination of both. With this flexible program, it is possible to investigate the effect on equalizer performance produced by changing the cable characteristics and input pulse shape, as well as many arbitrary factors that influence the error rate calculation.

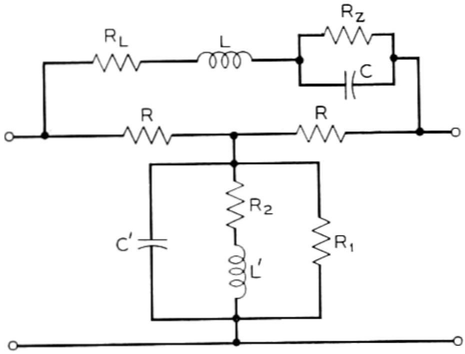

Fig. 3—Bridged-T equalizer section.

This program was the principal tool used in the initial design phase and it is still used for all investigations other than iterative optmization. The computational approach is to combine all the individual representations of the various sections into a single set of loss and phase data. An inverse Fourier transform is then evaluated to determine the equalizer pulse shape. From this pulse shape the eye opening and error rate are calculated. The ability to easily change representations is particularly valuable in allocating the design margins among the various sections of the system.

2.5 *Hybrid Simulation*

The equalizer was simulated initially on an analog computer because the time required for a digital calculation of the pulse response was too long for effective human interaction. The parallel operation of the analog components provides a rapid evaluation of the time response of continuous systems. Thus, the designer can modify equalizer parameters or circuit configurations while watching the effect on the pulse response. This ability to rapidly interact with the simulation enables the designer to develop intuition about the circuit operation and apply this knowledge to improve the design. This interactive capability was unique on the analog computer at the start of the design phase. Today, faster digital computers with graphic display devices can also provide some of this interactive capability.

The digital computer was first connected to the analog in a hybrid simulation to generate realistic dispersed pulse shapes for equalization so that the designer could observe immediately the influence of parameter variations on equalized pulse shape. This simulation was limited in its application because a more representative criterion, such as error rate, was required to properly weight all factors influencing the design. When more powerful digital computers became available, they were used to process the data from the analog computer in order to compute the error rate. Finally, a more modern hybrid made it possible to implement an automatic optimization strategy.

Since optimization was of prime importance, it was necessary to keep to a minimum the number of parameters to be adjusted. If this was not done, the time required for convergence to an optimum could become excessive, thus again making the human interaction ineffective. The bridged-T sections were represented by a single zero, two pole network rather than simulation of the actual configuration. This approximation assumes that the series and shunt arms are correctly matched. The use of a simplified representation, of course, requires that the optimized parameters later be converted into the component values for the bridged-T networks. A digital program was written that selected from standard parts lists the component values nearest the values computed from the optimized parameters. The sections of the equalizer that were not to be optimized were simulated by considering the actual network configuration. This was done so that the models used could be made to conform to the measured device parameters, particularly, the diodes in the ALBO.

The program used for optimization was based on the general-purpose Hybrid Optimization Program (HOP)[3] that was modified specifically for T2. For each equalizer, an ALBO was designed manually and then the fixed equalizer sections were optimized automatically. The block diagram of the hybrid simulation of the equalizer is shown in Fig. 4. The optimization program allows for up to eight different cable lengths (that are representative of the range of application of the equalizer) to be used in designing the fixed equalizer. The Pulse Transmission Program described in Section 2.4 is used to generate the unequalized pulses that would occur with each cable. Each input is used to drive the equalizer simulated on the analog computer with the adaptive section properly adjusted for that cable. To evaluate the effect of thermal noise on each equalizer design, an impulse is used as an additional input. The equalized pulses are sampled and the thermal noise computed from the sampled impulse response; these are used to compute error rate on the digital computer. The worst of the eight individual error rates is used as the measure of performance for each equalizer.

An initial equalizer design is determined manually because the engineer must provide a reasonable starting point for the optimization strategy. The Simplex[3] strategy is used to select the next parameter set specifying an equalizer, and the entire process is repeated until the relative improvement in performance is below a pre-selected limit. The strategy requires only a scalar performance measure for each design and does not require that derivatives be computed as in a gradient search procedure. Thus, it is much less sensitive to measure-

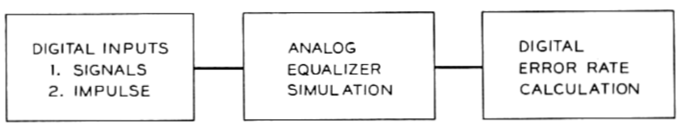

Fig. 4—Hybrid equalizer simulation used for optimization and tolerance analysis.

ment errors inherent in analog simulation. For an n parameter optimization, $n + 1$ designs must be evaluated initially. The procedure iteratively replaces the worst of the $n + 1$ designs by another design which is chosen along the line connecting the worst point with the center of gravity of the other designs in the n-dimensional parameter space. The best position along the line is determined by iteratively evaluating designs found by operations such as "reflection" about the center of gravity, "contraction" toward it, or "expansion" away from it.

This design strategy resulted in a set of equalizers that satisfied all requirements for the field trials. A final design phase will be necessary after the information gained in the field trials is taken into account. For this final phase a digital optimization program has just been written that provides data that is accurate and precise. A flexible simulation was no longer required for human interaction as the configuration has been chosen. Thus, it was possible to write a fast, digital analysis algorithm for this restricted application.

III. VARIABILITY ANALYSIS

Throughout the design phase, the engineer has been concerned with the realizability of the configuration and its sensitivity to parameter variations. Once the design has been optimized, it is necessary to verify that the performance will still be adequate when manufacturing limitations are considered and that the component tolerances are correct.

Tolerance analysis[4,5] is required because the optimized parameter values cannot be exactly realized in manufacture. The parameter values are not exact because components are usually available only in discrete ranges with a statistical spread in each range that is dependent upon the manufacturing process and the component's age.

Even after extensive analysis, it is still necessary to measure the performance of the actual circuits. First, prototype circuits must be tested to be sure that the predicted performance has been obtained. Each manufactured circuit must then be tested to ensure that it has been properly assembled. The computer can aid in diagnosing if predictions are not realized and also in automating the factory test procedures.

3.1 *Tolerance Analysis*

The Monte Carlo approach to tolerance analysis consists of simulating the system under investigation, randomly perturbing the parameter values and displaying the distribution of a scalar performance measure. With this approach, the influence of component variations on the nonlinear, error rate performance measure could be investigated with fewer assumptions and approximations than required with more analytical approaches. The most severe shortcoming with this approach is the amount of computer time required to acquire statistically significant information. Since analysis time is as critical as in optimization, the same hybrid simulation was used. To reduce the number of analysis runs, the designer can interact with the computer while watching a graphic display of a histogram of the performance measure. Thus, he can quickly terminate unsatisfactory runs, and also recognize by the insensitivity of the display to new data when sufficient samples have been accumulated rather than always accumulating the amount of data required by a pre-selected confidence limit.

The influence of parameter tolerances on the error rate to be expected from a pulse equalizer was investigated to aid in establishing the manufacturing specifications for both the bridged-T sections and the adaptive sections. The computer program repeats the following sequence of operations and accumulates the distributions under the user's control. A set of perturbed component values for each design is selected from the random distribution specified by the nominal values and tolerances with the relationship:

$$X_{\text{perturbed}} = X_{\text{nominal}}(1 + \text{Tolerance} \times \text{Random Number})$$

where the random number in the range ± 1 is selected from a scaled distribution. The component distributions used in the subsequent investigation are described in Section 3.1.1. Simulation parameter values are computed from the perturbed sets—on the hybrid computer these are potentiometer values. Both an unequalized pulse and an impulse are applied to the analog simulation to determine error rate, as during the optimization phase. It is possible to evaluate the error rate for one design every five seconds with this simulation.

The discussion of the information obtained from tolerance analysis is divided into three parts. In Section 3.1.2 only the bridged-T sections are perturbed, with the adaptive loop open, to determine an acceptable set of nominal tolerances for the passive components. In Section 3.1.3 the adaptive section operating closed loop is used to determine how closely the ALBO diodes must be matched. Finally, in Section 3.1.4 a closed loop simulation is used with all components perturbed to determine anticipated yield and establish limits for a factory acceptance test.

3.1.1 *Component Distributions*[6]

One of the most difficult problems in tolerance analysis is to obtain meaningful component data. If only a relative comparison is required, it is sufficient to use crude approximations to the actual distributions; but when one attempts to accurately predict yields, exact data is required with temperature effects and aging taken into account. Since only relative comparisons between various sets of tolerances were required for the analysis described in Section 3.1.2, all passive component values were assumed normally distributed with the nominal values as the mean. The standard deviation of the distribution was set equal to one-half the specified tolerance.

For proper closed loop operation of the ALBO, it is important that both sections act together to provide the correct pulse shaping. Unless the dynamic resistance of the individual diodes, used to provide the variable resistance, is approximately the same function of the control current, this tracking cannot be maintained. To provide adequate tracking, it was decided to select a set of matched diodes. The cost of matching a set will, of course, depend on the allowable resistance range within a set. Tolerance analysis was used to determine whether unusually tight control had to be established or standard production line techniques would be adequate.

The diodes are to be matched based on their measured resistance at two values near the upper and lower limits of control loop current. The matching operation was simulated in two steps. The first diode in each set was specified by choosing a pair of resistance values from measured distributions for that diode type. The two values could be selected independently because the resistance at the high current level depended primarily on the bulk resistance of the material while the bulk resistance is swamped by the normal diode resistance at the low level. The remainder of the set was obtained using two uniform distributions, having the specified matching limits, centered on the first pair of resistances.

The diode matching limits were chosen to reflect not only the original matching but also the changes that would occur with temperature and aging. For example, if the original match is assumed to be two ohms, the range may broaden to six ohms because of these effects. The tolerances on the passive components were the same as those used in Section 3.1.2.

After all tolerances had been specified for the components, additional investigations were performed to determine anticipated yield and performance variations that could be expected with a typical set of tolerances. The component types were chosen after discussions with the potential manufacturers, and then distributions were selected based on the data available for these types. Since the inductors are the most expensive component, it is desirable to use the widest tolerance possible. With wider tolerances, it is important to carefully model the limiting distributions. Since the worst-case limits for aging are large, the inductor tolerance model included separate nominal and aging distributions.

3.1.2 *Bridged-T Tolerance*

First, the component tolerance in the bridged-T sections were investigated to determine the relationship between various sets of passive tolerances and variations in error rate. It was assumed that these sections are correctly terminated and that all other circuit parameters are set to their nominal values and the control loop is not active. All the components in the basic bridged-T equalizer section shown in Fig. 3 may have tolerances applied to them except the resistors labeled R, which set the characteristic impedance. To simplify the analog simulation, these resistor values were equated to the termination resistances that were not to be perturbed. In a tolerance analysis simulation, it is important to avoid programming simplifications that, although correct when nominal values are used, may not be valid when components are perturbed. For example, the bridged-T section can be analyzed as a second-order system if it is assumed that the series and shunt arms are properly matched. Since this match would be destroyed by the perturbations, a fourth-order simulation is required.

Let us consider the influence of the parameters on the error rate for one bridged-T section. Several sets of passive tolerances were investigated and the resulting histograms are replotted on probability paper in Fig. 5. On this paper, a normal distribution appears as a straight line with the standard deviation (σ) inversely proportional to the slope. The histograms with finite tolerances are clearly not normally distributed; thus, the sets cannot be compared on the basis of their standard deviations. The relative influence of the tolerance sets can be compared based on the yield at a selected error rate. If the threshold of acceptability for this equalizer were, for example, an error rate less than 10^{-10}, then with one percent tolerance on the Rs and Cs and three percent on the Ls, approximately 98 percent of the designs would be acceptable. With the low number of samples used to obtain this data, the absolute yields may not be accurate but a relative comparison is valid. In examining these data, it is observed that a finite σ exists with no perturbations applied to the components; this is caused by the limited reproducibility of the analog simulation. This measure of reproducibility is valuable in determining whether the observed variability is produced by the programmed perturbations or machine errors. Since the equalizer was not optimized for this cable alone but for eight different cables, some designs with perturbed components produce error rates better than the nominal design.

The nonlinear nature of the error rate makes it difficult to estimate the effect of several bridged-T sections from single section histograms. This is illustrated in Fig. 6 which compares the histograms for each of the three bridged-T sections perturbed separately and all three simultaneously perturbed. The simultaneous perturbation of all three did not produce performance appreciably different from the worst of the individual sections (each section had different nominal component values). If one attempts to combine the individual section data to obtain a worst-case estimate of the overall three-section performance,

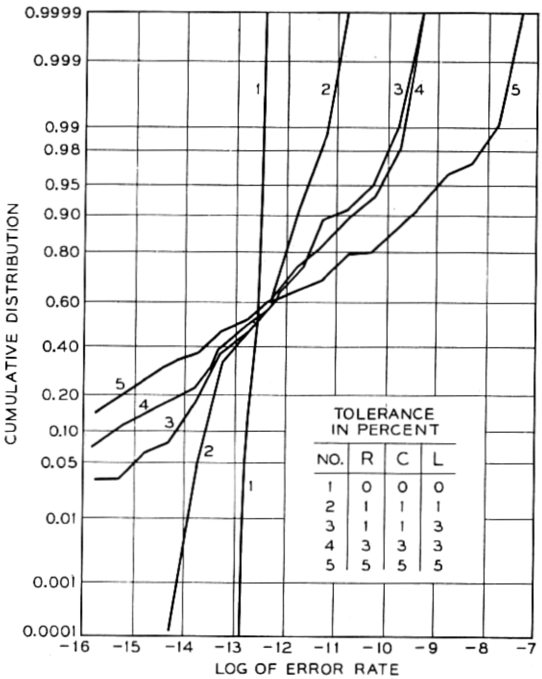

Fig. 5—Variation in error rate produced by applying component tolerances to one bridged-T section of a pulse equalizer.

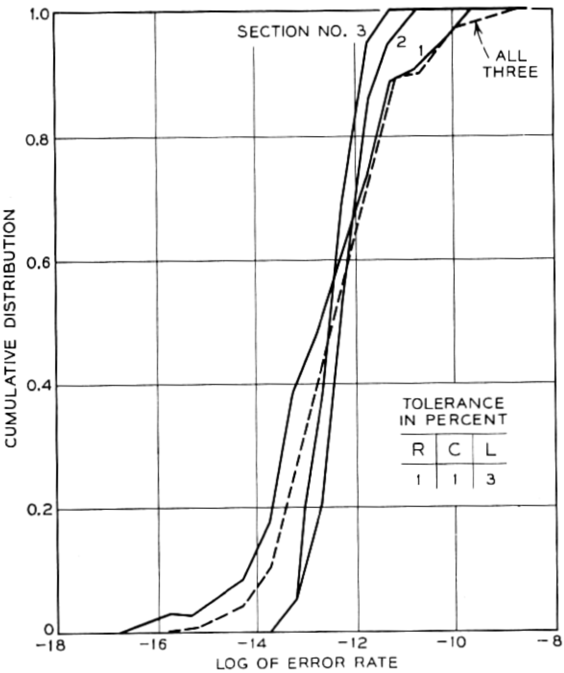

Fig. 6—Comparison of error rate variations produced by applying component tolerances to each of three bridged-T sections separately and to all three simultaneously.

a much more pessimistic estimate would result than the performance actually measured. If acceptable yields can be obtained with worst-case estimates, there is no need for measuring the distributions; but typically with "state of the art" designs, this is not the case and the use of actual distributions may allow the designer to relax some specifications and still obtain adequate performance.

As a result of these investigations, a set of tolerances were specified for the passive components in the bridged-T sections. The decision was based on allocation of margin, relative yields, and cost of various tolerances. It was verified that adequate performance could be obtained with commercially available components.

3.1.3 *Adaptive Equalizer*

The simulation was modified to include the effect of the adjustment loop before investigation of the parameter tolerances in the adaptive section. The adjustment of this loop will essentially compensate for variations in the average value of diode resistance; thus, only diode mismatch would affect the error rate. For each perturbed design, a simple iterative procedure was used to determine a value of control current that would change the diode ac resistance and thus return the pulse peak to a reference level. The diode ac resistance is related to the control current by the model:

$$R = K_1 + \frac{K_2}{I}.$$

The coefficients K_1 and K_2 were calculated from each pair of resistance values specifying a diode. Then the resistance in the ALBO could be calculated for any value of control current.

The adjustment procedure consists of first determining a nominal current level for the unperturbed design that produces a reference pulse height. After the components are perturbed, the pulse amplitude is measured at the nominal current. The control current is then perturbed and the peak amplitude is measured again. The value of the control current to readjust the peak to the reference level can then be calculated. Since the relationship between control current and diode resistance is approximately linear in the region of adjustment, this iterative procedure produced satisfactory results. The iterative procedure lengthens the time to evaluate each design because several analog runs are required but the time is still less than ten seconds per design.

The results of a typical set of runs are summarized in Table I. Normal distributions were used on the passive components in the adaptive section with the standard deviation equal to one half the specified tolerance. From this data it is evident that the effect of diode mismatch is of secondary importance when compared to the effect of passive component tolerances. Additional runs verified that diodes matched to standard manufacturing limits would produce satisfactory

TABLE I—INFLUENCE OF ADAPTIVE SECTION TOLERANCES ON ERROR RATE

Diode Mismatch Ohms		Passive Tolerances %		Range of Variation in Log of Error Rate
R(20 μa)	R(1 ma)	R	L	
±100	±3	0	0	0.36
0	0	2	4	1.54
±100	±3	2	4	1.55

performance. Therefore, the cost of tightening the matching procedure was not justified.

3.1.4 *Entire Equalizer*

A complete simulation consisting of three bridged-T and two adaptive networks operating closed loop was used to estimate the error rate and eye opening to be expected with manufactured units. Component distributions that reflect the manufacturers' specifications were applied to a typical equalizer design and some of the results are shown in Figs. 7 and 8. The passive tolerances used were R—1.5 percent, C—2.0 percent and L—nominal 2.0 percent with 0.2 percent aging. The diodes were matched within six ohms at the high current level and within 200 ohms at the low level. Figure 7 reveals that for this equalizer connected to a specific length of reference cable, the error rate would never be worse than 10^{-27}. In Fig. 8, it is observed that the eye opening can be reduced from a nominal 77.5 percent to a 75.9

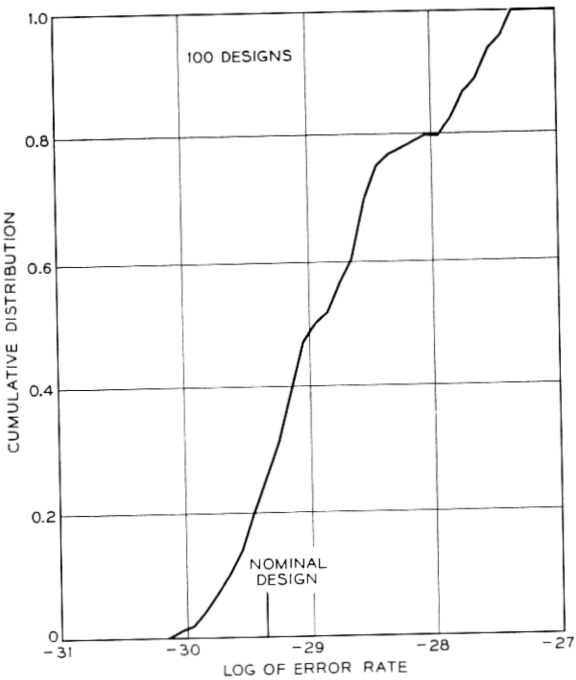

Fig. 7—Distribution of error rate resulting from application of typical manufacturing tolerances to all equalizer components.

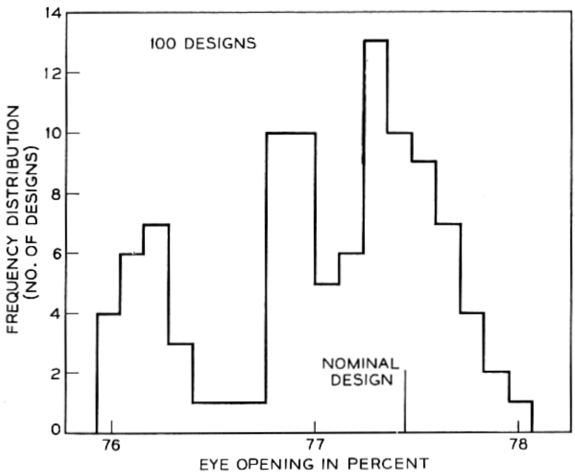

Fig. 8—Distribution of eye opening resulting from application of typical manufacturing tolerances to all equalizer component.

percent opening by component variations. Both these curves indicate satisfactory performance.

3.2 *Verification of Design*

Next we consider the computer aids available for verifying that the physical networks provide satisfactory performance. The approximations made in a simulation for computational efficiency are usually the reasons that disagreements between predicted and actual performance occur. For example, simplified device models and idealized network topologies are used to reduce the dimensionality of the system of equations being solved and thus save time. However, the real world may not be adequately represented because all the variability in the device is not included and effects such as spurious coupling are either ignored or crudely approximated.

When prototype equalizers were constructed, the performance was significantly worse than predicted and thus the cause and corrective action had to be determined. To determine the cause of poorer prototype performance, the circuits were measured and their performance compared to predictions. The computer can greatly alleviate the tedium of this task by automatically reducing the comparison data to a form suitable for evaluation by the engineer. The isolation of problem areas usually requires a degree of engineering judgment that is difficult, if not impossible, to implement in a general sense on the computer. The engineer can often test the validity of his diagnosis, however, by modifying the computer models and determining if the predictions now correspond to the measurements.

In addition to making detailed comparisons of time domain waveshapes measured with an oscilloscope in the laboratory and computer predictions, computer-aided procedures were also used. The Computer Operated Transmission Measuring Set (COTMS)[7] was used to measure the insertion loss and phase of the entire equalizer and the individual bridged-T sections. These data were inserted in PTP, Section 2.4, to calculate the pulse shapes. For comparison the pole-zero configurations used in the design were also inserted in PTP. For example, it was determined by a comparison of the pulse waveforms from PTP that the data from an equalizer measured as a complete unit produced 20 percent more undershoot at the first sample point following the peak than was produced by its pole-zero configuration. However, the measurements of the individual sections when combined produced an undershoot only four percent larger than that produced by the poles and zeros. It was evident that individual section measurements when combined did not produce the same pulse shape either as an equalizer measured as a complete unit or as actually obtained in the laboratory. This indicated that some of the discrepancy might be due to spurious coupling paths between the sections of the equalizer. Similar combinations of measurements, computations, and laboratory results uncovered other problem areas. Improvement in computer models, rearrangement of component layout, and the introduction of shields resulted in pulse waveforms that agreed very closely with computer predictions.

3.3 *Manufacturing Test*[8]

A fundamental difference normally exists between the techniques used to evaluate the performance of a circuit during the design phase and during manufacture. One strives for reality at all cost during design but wants an inexpensive test in the factory. For computer-aided design, one selects a performance measure, such as error rate or eye opening, that reflects how the circuit will function when installed in a system. For economic reasons, however, normally only a few simple tests on individual circuits are performed during manufacture. Since it is usually difficult to devise a simple test that will be indicative of system performance, the factory test may not detect all units that would fail in service and/or may cause a rejection of units that would be acceptable in the field.

To insure that proper selection is made, it is desirable to use similar performance measures in the design phase and in manufacturing test. The cost of maintaining and using complete systems to test individual circuits and the difficulty in simulating worst-case field conditions has made this approach unacceptable in the past. Now in some cases it is feasible to use the design measure and test under worst-case conditions using computer-operated test facilities (COTMS). The computer that controls the measurements can also contain a program that converts the measurements into the system performance measure. This is accomplished by storing in the computer a representation of the remainder of the system that corresponds to the worst case. This stored data is combined with data measured for a particular circuit and the performance measure calculated. The stored representation makes it possible not only to simulate worst-case field conditions at the manufacturing level, but also to take system modifications that occur into account by simple software changes.

To efficiently run the test procedure on the small computer in COTMS, it was necessary to develop a fast algorithm that required limited storage. The PTP program served as a basis for the eventual algorithm. To improve the run time, the generality in the input structure was removed and all data except for the equalizer were precalculated. The computation of the complete pulse shape was replaced with a search algorithm that located the pulse peak. Then only those samples of the pulses needed in the computation of the performance measure were calculated. It was possible to develop a fast search algorithm because the approximate peak height and location are known from the prototype measurements. If the waveshape deviated significantly from the prototype, the equalizer must produce unacceptable performance. Additional time was saved by basing the test on eye opening rather than error rate.

This procedure has been used to measure manufactured equalizers. The acceptability limits on eye opening to satisfy system requirements were determined after considering the effect of the component tolerances, as displayed in Fig. 8, and performing a tolerance study of the influence of measurement precision.[9] The running of the test procedure for each equalizer requires approximately $1\frac{1}{2}$ minutes. The program also provides an interpretive dialogue that tells the COTMS operator what to do and when; thus, the operator requires little specialized training. Furthermore, the measured data for each equalizer is recorded on tape so that subsequent field failures can be related to the performance at manufacture.

IV. CONCLUSIONS

A complete computer-aided design procedure has been used on the T2 equalizer. Initially the computer was used only for analyzing the circuit performance. As more powerful computers became available, they were used to optimize the parameters and measure the influence of component tolerances. Finally, a manufacturing test that evaluated the equalizers based on worst-case system performance was developed. The procedure appears to be applicable to other systems.

When integrated circuits are used, it becomes increasingly important to accurately predict performance and perform optimization and tolerance analysis before construction. The cost of constructing experimental circuits and the time required for the construction make it unrealistic for the designer to use standard laboratory procedures. Rather than construct breadboards, the designer can use the computer to obtain similar information. Thus, the computer approach to designing realizable circuits may prove to be the most economical way to build equalizers and other complex circuitry.

V. ACKNOWLEDGMENTS

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