Evaluation of Message Circuit Noise

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The reduction and control of message circuit noise requires that its effects be quantitatively characterized. This is achieved by measuring some physical attribute of the electrical noise such that two noises that are judged to be equally interfering are assigned approximately equal numerical magnitudes. To give meaning to such magnitudes, the scale of measurement is related by way of subjective assessment into terms useful to telephone engineering. Pertinent to message circuit noise measurement is the characterization of the relative interfering effect of single-frequency noise components and the way the ear combines these components to indicate the total effect. The correlation between a noise measurement and its associated over-all end-effect may be made by finding the transmission-loss equivalent of the noise being measured or by the direct application of telephone-user opinions expressing degree of transmission satisfaction. In addition to these topics, this paper discusses certain engineering aspects of noise evaluation.

I. INTRODUCTION

From the time of the first commercial telephone system, transmission engineers have been concerned with the problem of message circuit noise evaluation. Prior to the turn of the century, progress was slow and limited to crude estimates because of the lack of means for performing measurements. One's hearing mechanism had to serve as the indicating meter, and the scale of measurement was simply one's expression of attitude concerning the noise.

Initially, the most accurate determination of noise magnitudes was through frequency analysis and computation. A given noise voltage was first analyzed into its spectrum, which was then weighted according to a predetermined curve that characterized the relative interfering effect of frequencies in the telephone channel. The total noise magnitude was then obtained by summing the weighted components on a power basis. A quicker but less accurate way was to make an over-all noise measurement. "Circuit noise" was simply compared by ear to a variable-amplitude tuned buzzer, but due to the lack of objectivity the measured magnitudes often tended to disagree because of differences between operators.

With the advent of electronic measuring devices the picture began to change. Vacuum-tube voltmeters, with square-law detectors and associated circuitry to simulate weighting characteristics, would assign approximately the same magnitudes to noises producing the same order of interference. This was a significant advance, since it enabled the introduction of uniform yardsticks to give value-type interpretations of the severity of interference associated with each measured magnitude. The original yardstick was based on the concept of "noise transmission impairment," and subjective tests were performed to relate any given noise magnitude to an equivalent transmission loss.

Since that time, which dates back to the early 1930's, electronic noise measuring sets, their use, and the interpretation of measured magnitudes have undergone change. In addition to these changes, the operational nature of noise evaluation requires that many of the techniques and ramifications be constantly re-examined. It is not surprising, therefore, that the following questions are often asked:

i. How does *this* noise set measure a given noise?

ii. What are the units? Must a correction factor be added?

iii. Where is the best place to make the measurement?

iv. What type of measurement should be made?

v. What does the measurement mean operationally? What is considered a tolerable magnitude?

While much has been written on the subject, a large part of noise practice exists only in specialized reports on specific problems. To relate this knowledge and experience is, of course, beyond the scope of this article. Our purpose, rather, is to present a tutorial treatment of the most important historical, theoretical and practical aspects of message circuit noise evaluation.

We begin by discussing the fundamental problem: the measurement of circuit noise such that noises having equal "interfering effect" are assigned equal magnitudes. Pertinent are the concept of frequency weighting (i.e., the characterization of noise effects versus frequency); the manner in which weighted components combine; and the units of noise measurement. Background is provided on the choices over the years of reference for noise measurement and the effects of these references on numerical noise magnitude.

Next, the discussion follows the historical development of noise measuring devices, starting with a review of the features of the earliest device and ending with the 3A Noise Measuring Set.*

Highlights of the quantitative aspects of noise evaluation are then reviewed. Emphasis is placed on noise originating outside the telephone system, the application of the "telephone influence factor" to predict power system noise influence, and the use of noise measuring sets to estimate longitudinal and shunt unbalances in open-wire lines and cable pairs, assuming that external induction exists.

Finally, we consider the assessment of noise magnitude from the subscriber's standpoint. The discussion is centered on the use and relative merit of noise transmission impairments and "grade of service."

II. BASIC CONSIDERATIONS IN NOISE MEASUREMENT

2.1 *General*

An electrical disturbance in a telephone circuit — that is, any signal that does not convey intelligence — appears acoustically as *noise* at the output of the receiver of the telephone instrument. As noise capable of detection by the ear, it may be barely audible or it may be obtrusive enough to impair the reception of a telephone message. Noise is "high" when it is bothersome; it is "low" when its effects are insignificant. Thus, the evaluation of message circuit noise must concern itself with a quantification of noise based on the subjective reactions experienced by telephone users.

To achieve this objective, it has been found appropriate to perform these two operations:

(a) measure some physical attribute of the electrical noise such that two noises that are judged to be equally interfering are assigned approximately the same numerical magnitude; and

(b) subjectively assess the severity of the interference associated with each magnitude on the resulting physical scale, and relate the assessment into acceptability criteria such that the scale of measurement becomes useful to telephone engineering.

These two steps broadly define the underlying principles of message circuit noise evaluation: the first prescribes the way noise is to be meas-

* The 3A set is covered in detail in a companion paper.[1]

ured; the second provides the information necessary to the interpretation of the measurement.

In general, however, conversation over a telephone may be rendered more difficult not only by the presence of circuit noise, but also by the presence of room noise in the location of the telephone, the reaction of a particular subscriber, the way he uses the telephone and the volume level of the telephone conversation itself. Although it is impractical to incorporate accurately all of these parameters, the principle of measurement and the method for the subjective assessment of magnitudes allow, to a good approximation, for these additional effects.

From the measurement standpoint, it is sufficient to assign equal noise magnitudes on the basis of *moderately bothersome* noises that are judged to be equally interfering in the presence of *average* levels of received speech volume and room noise. Two characterizations are necessary: a "weighting function," which characterizes the relative interfering effect of single-frequency noise voltages, and a law of summation expressing the manner in which the weighted frequencies combine to produce the total effect. The weighting function is derived by evaluating and combining the relative annoyance of moderately loud single frequencies in the absence of speech and the relative impairment of speech by these frequencies, when the speech is at the average received volume level. The desired noise magnitude is obtained by weighting a given noise spectrum in accord with such a weighting characteristic, and then integrating the weighted spectrum by the associated law of summation.

Step (b) enables one to account for the effect of all other conditions of electrical circuit noise, received speech volume and room noise. This requires a multidimensional relationship expressing the degree of satisfaction, or degradation for the range of noise magnitudes (which result from the manner of assigning values as described above) in combination with any given levels of received volume and room noise.

2.2 *Frequency Weighting Characteristics*

Speech is impaired by the coincident presence of one or more foreign sounds. The mechanism is such that while one is listening to one sound the ability to listen to another is reduced — the degree of reduction being dependent on the relative amplitude of the two sounds. Quantitatively, sounds of frequencies below 900 cycles have a tendency to impair their adjacent higher frequencies rather than their adjacent lower frequencies. Above 900 cycles this effect is not as pronounced. However, maximum impairment always occurs near the frequency of the impairing sound.

Annoyance, on the other hand, refers to the subjective discomfort caused by noise during the absence of speech. It may be considered from the standpoint of loudness. As the volume level of a sound is increased, the louder and thus more annoying it becomes, although the effect is not directly proportional.[2] At low volumes, a high-frequency sound tends to be more annoying than a low-frequency sound, whereas at high volumes all frequencies tend to become equally annoying.

Theoretically, therefore, a particular weighting will characterize the effects of noise versus frequency only at specific volume levels. From a practical standpoint this is not a serious drawback. Consider, for example, the Fletcher-Munson loudness contours[3] shown in Fig. 1. Notice that, if the various noise components per cycle are confined to an approximate 25-db range, then the relative loudness does not change appreciably. Likewise, the change in the impairment mechanism of single frequencies is not appreciable over this range. Because of rigid noise

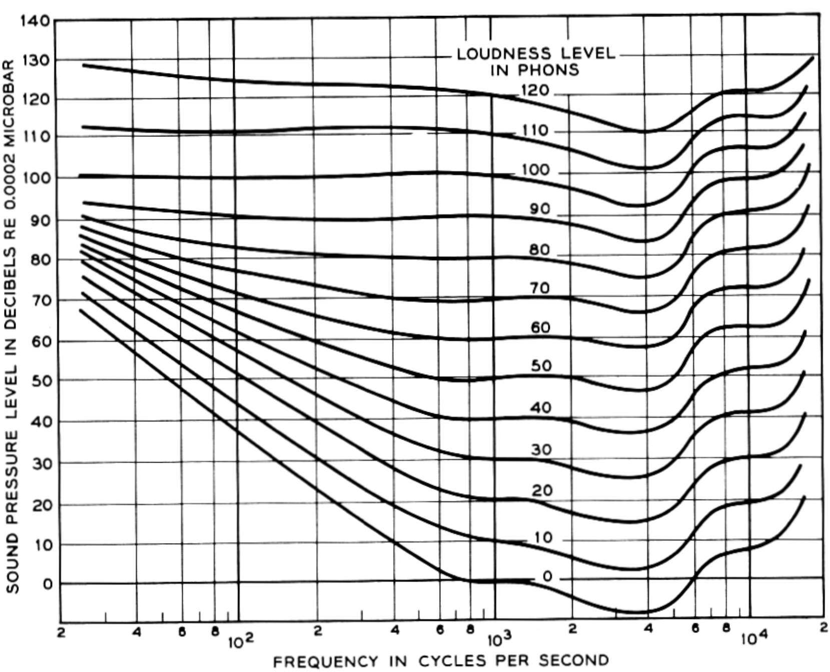

Fig. 1 — Free-field Fletcher-Munson equal-loudness contours for pure tones.

control throughout the Bell System plant, the 25-db range is usually not exceeded. Hence, it is the practice to use only one weighting characteristic for all applications, where such a characteristic is determined relative to some moderately bothersome level encountered in practice.

Throughout the years, weighting characteristics have changed with the gradual improvement of the telephone set. The first standard weighting characteristic used in an electronic measuring set, called the 144-line weighting, related to the deskstand telephone set prevalent during the 20's and early 30's. The second, called the F1A-line weighting, related to the 302 set and the third, called the C-message weighting, relates to the present 500 set. Although each of these was determined by a different subjective evaluation technique, they all incorporate the impairment and annoyance effects of noise for average conditions of message circuit telephony.

Since the determinations of the 144 and F1A weightings are well documented,[4,5] it is sufficient to describe briefly the technique for the derivation of the present C-message weighting. Two tests were conducted, one in the absence and one in the presence of speech. In the absence of speech, groups of observers were asked to adjust the loudness of 14 different frequencies between 180 and 3500 cycles until the sound of each was judged to be equally annoying as a −59-dbm 1000-cycle reference tone. Then, in the presence of the average level of received speech volume, the same groups of observers were asked to adjust the level of each of these frequencies so that the impairment on the speech tended to be equivalent to that produced by the 1000-cycle reference tone. The outcome was essentially a quantification of single-frequency noise impairment in terms of equal transmission quality.

In both cases, the various single-frequency levels were measured into a 900-ohm resistance, which was substituted for the 500 set. The results of each of these tests were averaged at each frequency, combined and smoothed as shown in Fig. 2. Notice the dip in the relative impairment characteristic in the neighborhood of 500 cycles. Here it is reasonable to assume that the individual frequencies were masked to some extent by the speech spectrum of the talker.

2.3 *Law of Combination*

As is well known from loudness considerations, the integrating characteristics of the hearing mechanism are highly complex. In particular, the mode of integration is amplitude-dependent and influenced by masking. It has been found, however, that weighted noise components are added approximately as power, provided the noise is confined to rela-

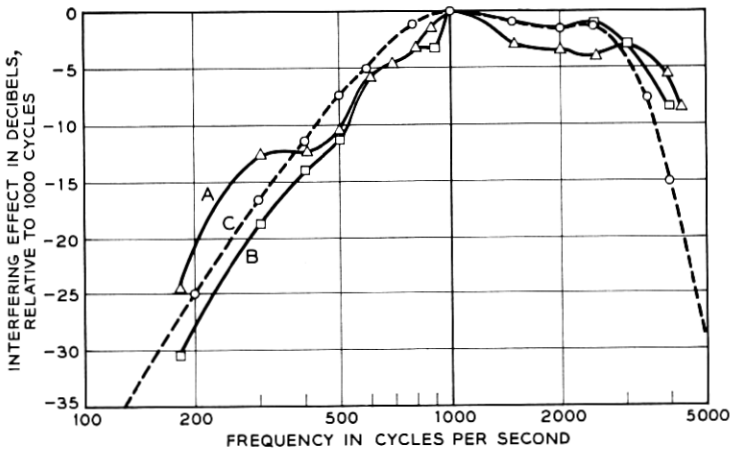

Fig. 2 — Interfering (subjective) effect in decibels of various single frequencies relative to the frequency (approximately 1000 cycles) of maximum interfering effect: A, interference due to impairment; B, interference due to annoyance; C, adopted combined effect.

tively low levels. Since this is usually the case, power addition is most appropriate.

While power addition is consistent with Fletcher's law of loudness addition for low-level weighted signals, early articulation studies of the effects of two or more noises also showed that the combined noise effect adds on a root-sum-square basis.[6] The latter was further borne out by subjective correlation of a number of noise measurements made with the F1A-line weighting characteristic using square-law detection.[5] Thirteen different types of noise that were judged to be equally interfering measured substantially equal in magnitude, as shown in Fig. 3. For comparison, the particular F1A-line weighted power measurements are indicated in decibels relative to open-wire line noise.

Further justification for the use of power addition was recently established in tests to determine the applicability of the C-message weighting. Different pairs of moderately interfering bands of thermal noise were presented to a group of observers who were asked to change the level of one until it was equal in interference to the other. These same bands were also compared objectively, by computing the differences between their weighted spectra on a power ($10^{db/10}$), voltage ($10^{db/20}$) and high-level loudness ($10^{db/40}$) basis.* The average subjective decibel differences in interference were found to agree remarkably well with the computed

* These three modes of summation are good approximations to Fletcher's law of loudness addition for low-, medium- and high-level weighted signals heard over the telephone.

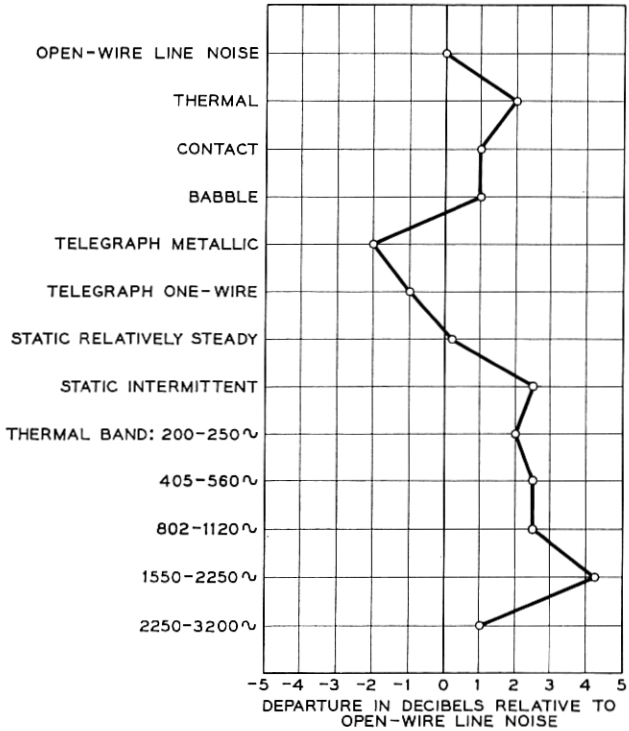

Fig. 3 — Difference between F1A-line weighted noise measurements for noises judged to be equally interfering.

differences based on power addition, whereas correlation for voltage and high-level loudness addition was poor.

2.4 *Units of Noise Measurement and Noise Magnitudes*

While a weighting characteristic and its companion law for the summation of weighted components essentially prescribe the way message circuit noise is to be measured, one must also be provided with a noise reference and a scale of measurement. At the time of the ear-balance (i.e., acoustic comparison) method of noise measurement, the unit of measurement was simply the "noise unit." It was defined to be equal to 10^{-6} of the current output of a 240-cycle buzzer, which served as the comparison standard. The value of current above this amount was numerically equal to the number of noise units.

With the advent of electronic noise measuring sets, the scale was changed to the decibel scale, and a reference of 10^{-12} watts of 1000-cycle power at the input (i.e., -90 dbm) was proposed for the reference of measurement. Based on this reference, the unit of measurement came to be known as the "dbrn" (decibels above reference noise).

Two considerations were pertinent to this choice of reference: the power level was chosen to be sufficiently low so that when noise was measured the results would be positive numbers of reasonable size; and the choice of the 1000-cycle frequency corresponded to the normalized zero loss point of the 144-line weighting prevalent at that time.

Shortly thereafter, the introduction of the 302 set resulted in the need for a different weighting. This set was much flatter in frequency response than the older deskstand telephone, and the 144-line weighting could not be applied. After completion of the work that led to the previously mentioned F1A-line weighting, it was felt that something should also be done about the reference of measurement. The newer line weighting admitted a substantially wider band of frequencies and for the same reference the two weightings would measure a given noise numerically different. Tests showed that with the newer weighting the result was about 5 db higher for several types of noise, including 3 kc thermal noise.

To bridge this gap, a new reference was proposed in conjunction with the newer weighting characteristic. This reference (i.e., zero on the meter) was a 5-db upward adjustment, from 10^{-12} to 3.16×10^{-12} watts of 1000-cycle power, or from -90 dbm to the 5-db-less-sensitive -85 dbm. Hence, for a uniform 3-kc band of thermal noise one would now obtain the same numerical magnitude of measurement with either weighting. On the other hand, while the old reference required 10^{-12} watts of 1000-cycle power to give a zero indication on the meter, 3.16×10^{-12} watts, or 5 db more of 1000-cycle power, would be needed to give a zero indication with the new reference. To distinguish between the two references, the newer one was designated "dbrn adjusted" or "dba."

At the present time, the picture has further changed. The introduction of the 3A Noise Measuring Set with its new C-message weighting posed a similar problem regarding its reference for measurement. This weighting, as will be seen, has a wider equivalent spectrum than the F1A-line weighting. To follow the approach described above would require a still higher equivalent reference in order to obtain the same numerical measurement for 3 kc thermal noise. Although this step was considered, it was deemed unwise for with a higher (less sensitive) equivalent reference, many of today's low noise levels would be assigned "negative" magnitudes.

To circumvent this possibility, it was decided to return to the basic 10^{-12} watt reference, that is, to -90 dbm. This reference, although numerically equal to the original dbrn at 1000 cycles, is not its equivalent when viewed in terms of weighted noise measurements. While this latest reference is called dbrn, in actual fact it is "dbrn C-message" to distinguish it conceptually from "dbrn 144-line." For instance, as will be shown later, 3 kc band-limited random noise will read 6.5 db higher with C-message weighting than with 144-line weighting. In the case of an F1A-line weighted noise measurement, both the weighting characteristic and the different reference (dba versus dbrn) will affect the results.

The relationships can best be illustrated with some examples. The three different weighting characteristics are shown in Fig. 4. Since these curves reflect relative subjective noise effect (or relative interfering effect), the maximum of each curve is normalized at 0 db. Note that the maximum of each curve occurs at approximately 1000 cycles.

Consider now the measurements that would be obtained for two extreme cases of noise: (a) a 1000-cycle noise voltage and (b) a random noise voltage. The former is relatively easy. We need only compare the given signal to the reference of measurement, since a 1000-cycle signal suffers no weighting. For illustration, let us assume a 1000-cycle voltage such that the noise power is 10^{-3} watts at the input of a noise set, capable of each of the three measurements. We would obtain the following

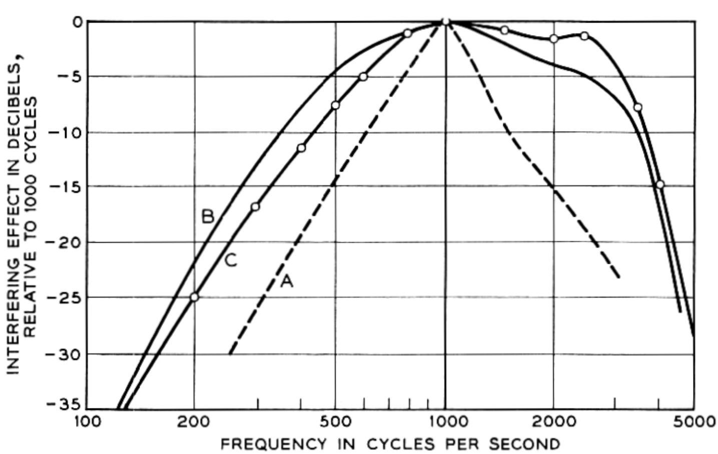

Fig. 4 — Response vs. frequency of: A, 144-line weighting; B, F1A-line weighting; C, C-message weighting.

noise levels:

$$N_{\text{dbrn}(144)} = 10 \log_{10} \left(\frac{10^{-3}}{10^{-12}} \right) = 90 \text{ dbrn},$$

$$N_{\text{dba}} = 10 \log_{10} \left(\frac{10^{-3}}{3.16 \times 10^{-12}} \right) = 85 \text{ dba},$$

$$N_{\text{dbrn (C-message)}} = 10 \log_{10} \left(\frac{10^{-3}}{10^{-12}} \right) = 90 \text{ dbrn}.$$

Now consider the application of the three weighting characteristics to a random noise voltage whose power spectrum $p(f)$ is rectangular and confined to a 3-kc band. To determine the three noise measurements, it is sufficient to compare the total unweighted power P to each of the three weighted powers $P_i'(i = 1, 2, 3)$ and express these differences on a decibel basis.

For the assumed power spectrum, $p(f)/3000$ is constant per cycle, say p, at the input to our hypothetical noise set. Thus the weighted powers P_i' are given by

$$P_i' = p \int_0^{3\text{kc}} w_i(f)\, df,$$

where $w(f)$ is a particular weighting characteristic, expressed as $10^{\text{db}(f)/10}$ to comply with the power addition requirement for weighted noise components. In this notation, the values db(f) are simply the relative subjective effects provided by each of the three weighting curves on Fig. 2. Thus the reduction in input power suffered by weighting is given by

$$10 \log_{10} \left(\frac{P}{P_i'} \right) = 10 \log_{10} \left[\frac{3000}{\int_0^{3\text{kc}} w_i(f)\, df} \right].$$

The problem of solving the integrals $\int_0^{3\text{kc}} w_i(f)\, df$ is readily facilitated by numerical approximation. Fig. 5 shows the three weighting curves transformed from relative decibels to numerics, $w(f) = 10^{\text{db}(f)/10}$.

Since $w_i(f)\,|_{f=1000} = 1$, the area under the line $w(f) = 1$ from 0 to 3 kc must equal 3000 square units. Hence, if we let this area be A and the areas under $w_i(f) = A_i$, then the reduction in power due to weighting is:

$$10 \log_{10} \left(\frac{A}{A_i} \right).$$

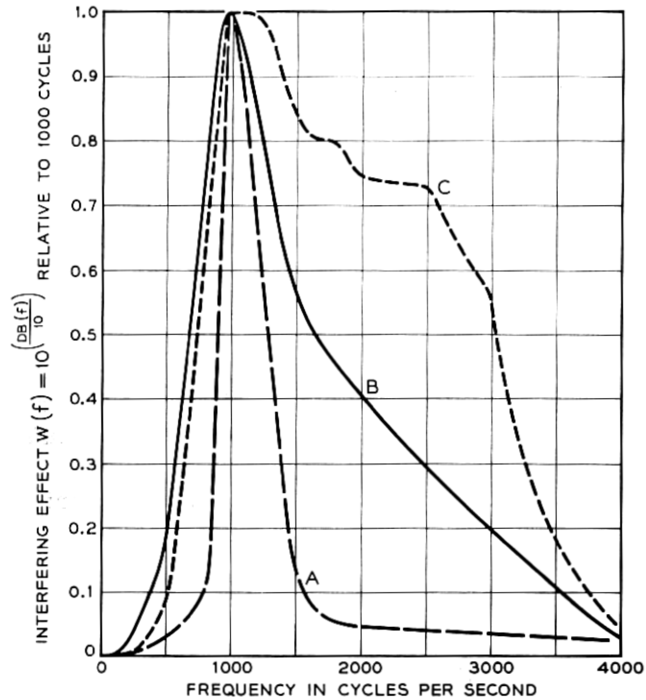

Fig. 5 — Result of transforming the three weighting characteristics shown in Fig. 4 from relative db to $10^{db/10}$: A, 144-line weighting; B, F1A-line weighting; C, C-message weighting.

It is found approximately that

$$A_1 = A_{144} \doteq \frac{A}{6.2},$$

$$A_2 = A_{\mathrm{F1A}} \doteq \frac{A}{2}.$$

$$A_3 = A_{\text{C-message}} \doteq \frac{A}{1.4}.$$

Hence the effect of the three weightings is to reduce a flat 3-kc spectrum by approximately 8, 3 and 1.5 db respectively. For example, given a flat 3 kc-spectrum that measures 10^{-3} watts at the input to our hypothetical noise set, the three respective noise levels are found to be:

$$N_{\text{dbrn}(144)} \doteq 10 \log_{10} \left(\frac{10^{-3}}{10^{-12}} \right) - 8 = 82 \text{ dbrn},$$

$$N_{\text{dba}(\text{F1A})} \doteq 10 \log_{10} \left(\frac{10^{-3}}{3.16 \times 10^{-12}} \right) - 3 = 82 \text{ dba},$$

$$N_{\text{dbrn}(\text{C-message})} \doteq 10 \log_{10} \left(\frac{10^{-3}}{10^{-12}} \right) - 1.5 = 88.5 \text{ dbrn}.$$

Evidently for other complex noise voltages these relationships are not valid. In general, given any noise $g(t)$, whose long-time average power spectrum is $p(f)$ (where $f_1 \leqq f \leqq f_2$), then the noise level of $g(t)$ is:

$$N_{\text{db(ref)}} = 10 \log_{10} \left[\frac{\int_{f_1}^{f_2} p(f)\, 10^{\text{db}(f)/10}\, df}{\text{reference power}} \right].$$

III. NOISE MEASURING DEVICES

3.1 *Early Devices*

It has been shown that a noise weighting characteristic, a companion law for the summation of weighted components, a reference level and a scale of measurement are all necessary to effect a meaningful measure of circuit noise. It will now be discussed how these basic requirements are, and have been, simulated in instruments to obtain the measurements directly.

The first apparatus for the measurement of circuit noise was introduced shortly after 1900. It consisted of a sort of acoustic comparator wherein the weighting and summation was achieved directly by ear. One first listened to the acoustical output of a telephone receiver connected to a "noisy" telephone line and then, by means of a switch, listened in the same receiver to a small inductor alternator generating a 240-cycle voltage. The intensity of the sound produced by the output of the altenator was adjusted by means of a potentiometer until the observer felt that the "interfering effect" of the alternator tone was the same as the "interfering effect" of the noise. The result of the measurement was expressed in microamperes in the telephone receiver. It may be observed that, in using this device, each "noise measurer" became an individual interpreter of the subjective-objective relation of noise.

Subsequently, the alternator was replaced by a battery-operated buzzer, which supplied a constant volume source of tone called a "noise standard." An additional improvement was made by providing the potentiometer with a numerical scale, graduated in "noise units."[7] This device, called the 1A Noise Measuring Set (see Fig. 6) did not, however, attain any greater objectivity than its predecessor. It remained on the scene until 1929, when it was superseded by the 1A Noise Amplifier (a device intended for noise measurement on toll circuits). The latter was the first to incorporate frequency weighting, and it employed the 6A Transmission Measuring Set as an indicating device. The elimination of the "noise measurer" as part of the measuring system was of considerable importance in that it eliminated most of the difference between operators.

3.2 *Electronic Noise Measuring Sets*

In accord with the principle of message circuit noise measurement, an ideal noise measuring device must simulate a procedure that will assure that two noises judged to be equally interfering are assigned the same numerical magnitude.

Thus, ideally, for any given noise voltage $g(t)$ the device must first separate $g(t)$ into its frequency components. This might be achieved by a series of bandpass filters, each with passband $\Delta\omega$. The device must then sense the variations in amplitude at the output of each filter to gauge the relative interfering effect of all components present. Then, by means of variable attenuation, each component must be weighted by an amount equal to its relative effect as determined by the previous operation. Next, the device must transform and sum the weighted amplitude components by a rule to indicate the total interfering effect of the original noise voltage $g(t)$. Finally, the outcome should be time-averaged over a period comparable to the hearing response and the resulting magnitude suitably indicated on a numerical scale as a function of time.

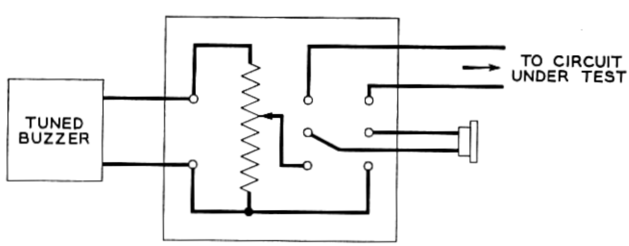

Fig. 6 — Schematic of 1A Noise Measuring Set. Potentiometer was adjusted until buzzer tone appeared to be equally interfering as noise on circuit under test.

From a practical standpoint, this simulation can be simplified as discussed in Section 2.1. The weighting process is simply achieved by a suitable network, the response of which approximates the interfering effect for the nominal range of noise levels encountered. For the transformation and summing process it is sufficient to use square-law rectification, which is appropriate for the noise levels of interest. Lastly, the rectified output, which is then proportional to the rms value of the weighted noise voltage, may be averaged over a specified period of hearing response and indicated on a dc meter that is calibrated in terms of input to the set in decibels from the reference of measurement.

Thus, operationally, all electronic noise measuring sets ought to behave in a like manner. The essential differences will be only in the type of weighting and the particular reference of measurement that appears to be appropriate, as well as in specific features that are dictated by the telephone system environment and special noise measuring needs. The latter refer mainly to the input arrangements and specific weightings, such as might be required in the measurement of program circuit noise or noise across the receiver.

One of the input arrangements of particular importance is the noise-to-ground input. Its inception dates back to the first major activity in noise evaluation: the inductive coordination of power and telephone systems, begun in 1912.[8] The investigators found that balance between the two sides of the telephone circuit at noise frequencies was an all-important factor. The power circuit induces comparatively high voltages to ground on each wire of the telephone pair. Unless the pair is well balanced, either longitudinally or to ground, these induced voltages will cause metallic currents in the transmission circuit. Even slight unbalances will result in such currents, which appear as metallic noise voltages across the terminals of the circuit. While it was realized that excessive metallic noise voltages of this type could be minimized by good maintenance and design, the means of guiding such mitigation required a noise set that would measure both "noise-metallic" and "noise-to-ground" accurately.

Although the ear-balance noise measuring sets were used to measure noise-to-ground (as well as noise-metallic), it was not until the advent of the electronic noise measuring set that these measurements attained the necessary sophistication and objectivity.

3.3 *The 2A — Forerunner of the 2B and 3A*

The 2A Noise Measuring Set,[9] introduced in 1937, was the first device that adequately realized the primary objective of message circuit noise measurement. It was portable, and went a long way to imitate the important qualities of the hearing mechanism discussed in Section II. A functional diagram of the set is shown schematically in Fig. 7.

This set consisted of various input circuits, a number of filters to simulate weighting characteristics (the basic one for noise measurements being the 144 weighting), an attenuator, a three-stage vacuum tube amplifier, a quasi-rms (copper oxide) detector for power summation of weighted components and a decibel meter with a 200-millisecond integration time* to indicate the noise level in dbrn. Additional features included a self-contained battery power supply, and means for internal calibration. While these components were designated primarily from the standpoint of noise measurement, the set had other capabilities. For example, means were also made available for volume and sound level measurements — two features that were later standardized in other primary measuring devices.

The input impedances were chosen to be compatible with the telephone system environment. A 600-ohm line input was provided for terminating noise metallic measurements on toll circuits. This input was designed to work with either the 144-line weighting or a flatter weighting suitable for the measurement of noise on 8-kc program circuits. In addition, a 2000-ohm bridging impedance was supplied to measure noise across the receiver (the latter being low impedance). The weighting for receiver noise measurements was a modification of the 144-line weighting, wherein the line-to-receiver transfer characteristic of the deskstand telephone was taken into account.

In addition to these three basic input arrangements, a 6000-ohm bridging input was provided to enable the measurement of noise-metallic on working telephone circuits. The input circuit for noise-to-ground consisted of 100,000 ohms in series with the line input. This arrangement presented a high input impedance to ground and reduced

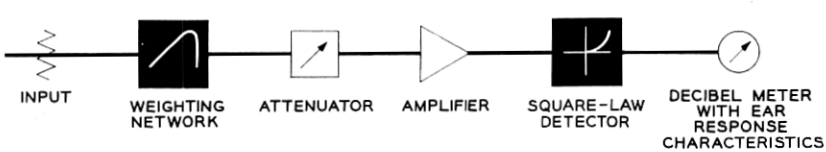

Fig. 7 — Schematic of 2A Noise Measuring Set.

* This is approximately the time required by the ear to appreciate the full loudness of a sound.

the sensitivity to make the indicated noise-to-ground magnitude comparable to the noise-metallic magnitude.

To make any of these measurements one simply connected the circuit under test to the proper input and adjusted the attenuator until the meter pointer gave a scale indication. The measurement was the sum of the attenuator setting and the meter indication. The former had a 60-db range, whereas the meter scale had an 18-db range. Reference noise in all cases was the meter reading (i.e., "zero") obtained with 10^{-12} watts of 1000-cycle power dissipated at the point of measurement. The actual minimum measurable noise was in the order of 10 dbrn.

The "sound input," in conjunction with a suitable microphone and matching transformer, permitted the set to be used for sound level measurements. While the minimum measurable level depended on the microphone and the transformer, the use of the standard 630A condenser microphone with the 111A repeat coil enabled the measurement of sound level as low as 55 db above reference. The weighting used in conjunction with such measurements corresponded closely to the "A" weighting currently found in sound level meters. The reference for sound measurements was chosen equivalent to 10^{-16} watts per square centimeter at 1000 cycles.

A major drawback of this set was that, for one-half of its 12 possible measurements, it was necessary to add various different correction factors to obtain the correct numerical magnitudes.

3.4 *The 2B and 3A Noise Measuring Sets*

In essence, the 2B Noise Measuring Set was a modified 2A. Introduced in 1941, it incorporated the F1A-line and the so-called HA1-receiver weighting for noise measurements in dba, two extra sound weightings, and improved means of internal calibration. The new noise weightings were needed because of the advent of the 302 telephone set, which had a different response characteristic than the earlier deskstand telephone set for which the 2A set with its basic 144-line weighting had been designed.

For simplicity, the two new weightings were obtained by changing the responses of the 144-line and receiver networks. The result was that the modified networks had an inherent loss 12 db greater at 1000 cycles than had had the original 144 networks. Since the reference level for F1A-HA1 weighted measurements was -85 dbm, compared to the reference level of -90 dbm for the two 144 weightings, the net difference in meter reading was 7 db. Unfortunately, this necessitated a variety of additional correction factors for all F1A-HA1 noise measurements — the basic one being 7 db for the F1A-HA1 line, receiver and noise-to-ground measurements.

In the new 3A this situation no longer exists. This set is a scaled-down version of the 2B, eliminating the volume, sound level, and receiver noise measurement features. It is direct-reading, making the need for corrections unnecessary. In addition, the set is smaller and lighter due to the use of miniature components and transistor circuitry. It is more sensitive than either the 2B or 2A, and has an improved quasi-rms detector enabling bridging, terminating and noise-to-ground measurements to zero dbrn with C-message weighting.

IV. QUANTITATIVE ASPECTS OF NOISE MAGNITUDE

4.1 *General*

In addition to the quantification of noise effects, message circuit noise evaluation also deals with noise studies and the control of noise to reduce its magnitudes to levels that do not unduly interfere with telephone service. The problem of control does, of course, hinge on a set of standards—the setting of which is guided by a correlation between subjective effect and measured magnitude. Once the standards are set, however, the quantitative interpretation necessary to noise control becomes a separate field of study. While it is not the purpose of this paper to include the setting of noise standards nor to discuss the engineering steps of controlling noise, it suffices to discuss some of the uses of noise sets that bear directly on noise studies.

4.2 *General Use of Message Circuit Noise Measuring Sets*

Whenever noise is measured on a telephone circuit, one should know the average speech volume level (vu) at the point of measurement. Lacking a specific measurement of vu, one should know the transmission level at the point of measurement from which speech volume may be inferred. Generally, in the case of long distance circuits, one refers the noise measurement to a 0-db transmission level (TL) point.

Since the noise measuring set is an audio-frequency device, noise may be measured at any accessible point in a voice frequency circuit. The circuit may be taken out of service and the measurement made with the line input of the noise set as a termination, or the measurement may be made on a bridging basis, where regular telephone equipment terminates the line that is idle at the time of measurement.

Noise measurements on carrier or radio channels must, of course, be made at the telephone circuit terminals where these channels operate at voice frequencies.

Last but not least, it is important to monitor each noise measurement. This is necessary to insure that noise is actually being measured and also to observe the character of the noise.

4.3 *Use of Noise Measuring Set To Estimate Telephone Influence Factor*

From the point of view of exchange plant telephony, an important external source of noise is that originating in power systems. This noise is important because, in general, it cannot be reduced to tolerable levels solely by transmission design (unless it is possible to separate power and telephone lines adequately). Because of this situation, the reduction and control of power line noise is and has been accomplished by joint engineering coordination with the power companies.

The most expedient approach is to attempt a solution prior to the actual construction of either a power or a communication facility. This requires an estimation of the amount of noise to be expected from the specified condition of the exposure prior to construction. A method that has been of great help is based on the concept of "telephone influence factor" (TIF).[10,11] This refers to either a voltage or current wave in an electrical supply system, and it is defined as the ratio of the square root of the sum of the squares of "weighted" rms values of all sine wave components to the rms value of the entire wave.

Thus

$$\mathrm{TIF} = \frac{\sqrt{\sum_{i=1}^{n} (A_i W_i)^2}}{A},$$

where A_i is the rms value of the (voltage or current) sine wave component at frequency f_i, W_i is the TIF weighting factor at f_i and A is the rms value of the entire wave.

The TIF weighting function $W(f)$ accounts for the relative interfering effect of single-frequency tones $w(f)$ in the message circuit (e.g., the 144-line, F1A-line or C-message weighting) and the variation with frequency of the inductive coupling between power and communication circuits. The new curve based on the C-message weighting is shown in

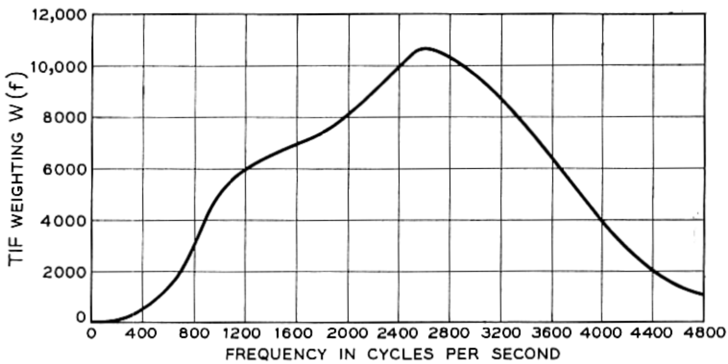

Fig. 8 — Proposed new TIF weighting curve, $W(f) = Kw(f)M(f)$, where K is such that W(1000 cycles) = 5000; $w(f) = 10^{\mathrm{db}(f)/10}$ is the C-message weighting and $M(f) = f/1000$ to approximate the coupling distortion between power and telephone circuits.

Fig. 8. Note that the weighting is given in numerics, with W (1000 cycles) chosen to be 5000.

The measurement of either voltage or current TIF is facilitated by using a noise measuring set (to give the subjectively weighted root mean square magnitudes) in conjunction with a suitable coupler (to provide for the effect of coupling versus frequency between power and communication facilities).[12] A schematic set-up for the 3A Noise Measuring Set is shown in Fig. 9.

Using the voltage coupler, the measurement will be proportional to the $Kv \cdot T$ product (the numerator of the voltage TIF expression):

$$\sqrt{\sum_{i=1}^{n} (V_i W_i)^2}$$

in dbrn, where V_i is the rms value of each sine wave component and W_i the corresponding TIF weighting factor (the latter resulting from the characteristics of the coupler and the C-message weighting). Simi-

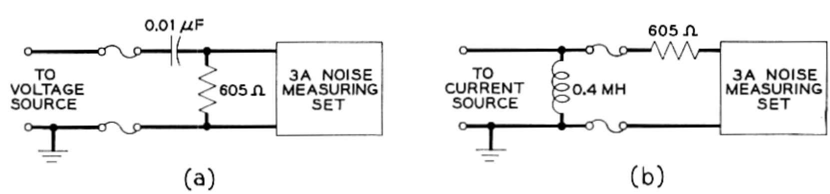

Fig. 9 — Set-up for (a) voltage and (b) current TIF measurements using new 3A Noise Measurement Set.

larly, using the current coupler, the measurement in dbrn will be proportional to the $I \cdot T$ product:

$$\sqrt{\sum_{i=1}^{n} (I_i W_i)^2}.$$

The relation between these measurements and the numerical $Kv \cdot T$ and $I \cdot T$ products is given by

$$Kv \cdot T = 10^{[N_v(\text{dbrn})-43.8]/20},$$
$$I \cdot T = 10^{[N_I(\text{dbrn})-20.2]/20},$$

where N_I and N_v are the corresponding 3A set measurements. Division of these numerical factors by the total rms value of voltage (in kilovolts) or current (in amperes) gives the over-all voltage or current TIF.

In early applications, these factors were used to estimate the noise induced in a given exposure. Today, the greater interest lies in assuring that ac and dc machinery (as manufactured) meet a certain conservative value of TIF.

4.4 *Other Special Uses of Noise Measuring Sets*

As mentioned in Section 3.2, there are two types of unbalances in wire systems that may permit induced "voltage-to-ground" to cause excessively large metallic noise voltages in the transmission circuit. These unbalances, called series and shunt unbalance are shown in their most elementary forms in Figs. 10(a) and 10(b).

In the case of Fig. 10(a), it is assumed that the presence of Z_{sh} does

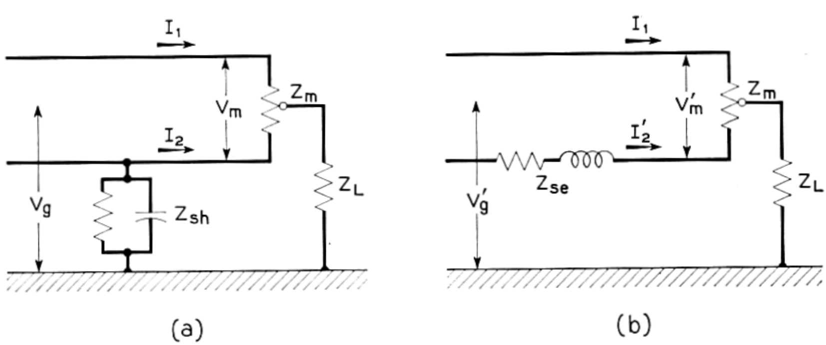

Fig. 10 — Equivalent circuit representations for (a) shunt and (b) series unbalance. For shunt unbalance, $20 \log_{10}(V_m/V_g) = 20 \log_{10}(Z_m/4Z_{sh})$ = balance ratio in decibels; for series unbalance, $20 \log_{10}(V'_m/V'_g) = 20 \log_{10}(Z_{se}/4Z_L)$ = balance ratio in decibels.

not affect the magnitude of V_g and, in the case of Fig. 10(b), it is assumed that the external source of induction is to the left of Z_{se} and that the Z_{se} is small compared to Z_L. Both unbalances are assumed to be single entities, and each is therefore an outstanding source of unbalance. Effects of phase shift and attenuation are not taken into account in this example.

A relative measure of these unbalances may be obtained by making noise-to-ground (N_g) and noise-metallic (N_m) noise measurements. For the 3A Noise Set, the standard N_g input arrangement is such that a N_g measurement is 40 db less sensitive than a N_m measurement.

Thus, if one measures both N_g and N_m, the balance ratio is given by

$$N_m - (N_g + 40) = \text{balance in db.*}$$

In the voice-frequency range, excellent balance performance is represented by ratios < -60 db; good by these between -60 and -50 db, fair by those from -50 to -40 db, and poor by ratios > -40 db.

Another quantity of interest is the severity of the induction itself. This is found by simply measuring N_g. For the new 3A Noise Measuring Set, values of $N_g > 40$ dbrn represent high noise influence, those from 20 to 40 dbrn represent medium noise influence, and those less than 20 dbrn represent low noise influence.

In addition to the above, the N_g input is also useful for measuring low-frequency voltages. These include both 25- and 60-cycle voltages, which are usually not audible. In estimating these components, it is necessary to measure first the weighted and then the unweighted (flat) noise with the appropriate networks. The difference between these measurements will give some indication of the extent of low-frequency induction.

V. SUBJECTIVE ASSESSMENT OF NOISE MAGNITUDE

So far we have considered only the ramifications involved in the design and objective use of a suitable noise measuring instrument. Consider now the subjective aspects of noise magnitude, which make the measurement of electrical noise meaningful from the telephone user's standpoint. As discussed in Section 2.1, this necessitates subjective assessments to determine the severity of interference versus noise level N_m. Once established, these assessments serve the telephone company as the means of controlling noise in the best interest of its subscribers.

The results of two types of assessments are currently in use. One set of results *measures* noise magnitude in terms of "equated transmission

* In the absence of an induced voltage V_g, this method will not yield a meaningful result. However, in such cases the existence of unbalances will be no problem.

loss"; the other provides expressions of attitude to noise as a function of magnitude in the presence of different amounts of received speech volume. Since these results are completely different in concept, they will be treated separately.

The first dates back to an early philosophy, which postulated that all factors that degrade a telephone conversation and make it poorer than face-to-face conversation, e.g., noise, distortion, sidetone and volume loss, should be expressed in similar units. As such, consideration could be given to the summation of the effects of these factors to produce a figure of merit indicative of the over-all efficiency of a given connection. To meet this desirable condition, it was decided that all factors that degrade transmission be subjectively quantified in terms of equivalent decibel transmission loss.[13]

Consider two identical message channels serving the same talker and listener. On one of these introduce x dbrn* of noise. The effect will be to degrade this channel relative to the channel with no noise. Now, if one slowly degrades the "no noise" channel by introducing flat loss, there will be some value of loss for which the two circuits are conceptually equal in degradation. The actual value, say y db, is said to be the *equated transmission loss* for the given noise level of x dbrn.

The original subjective technique for the determination of these equivalent losses for noise was the articulation test. In such a test the source was a talker who uttered various selected sentences over a variable-loss test circuit to a sample of telephone users (observers) in the presence of an average amount of room noise. In each sentence there was a meaningless syllable made up of three letter sounds. For different values of circuit loss, each observer recorded the letter sounds that he thought were present in the meaningless syllables. This process was then repeated at the nominal (no loss) volume, but in the presence of various amounts of circuit noise. Next, the percentage of correctly received letter sounds (percentage of articulation) was computed for all observers, at each value of circuit loss and at each noise level. These percentages were then plotted as articulation versus loss (no noise) and articulation versus noise level (no loss). Data indicative of this procedure using 500-type sets are shown in Figs. 11(a) and 11(b), where actual values of per cent are estimated in light of the results of the original work.[6] From such curves the equated transmission losses are obtained by finding at each noise level the corresponding circuit loss that gives the same percentage of articulation. For example, 40 dbrn (noise) $\approx$ 9.0 db (loss), as is seen by comparing the 86.5 per cent articulation score.

* From here on, all units of noise measurement are in dbrn C-message.

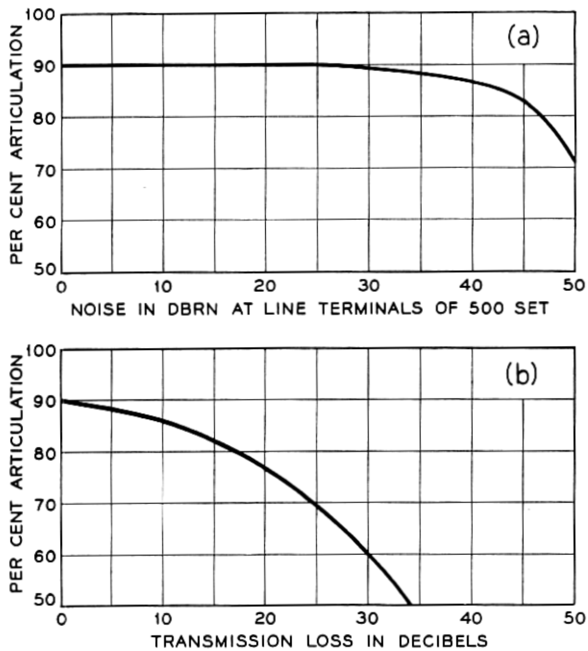

Fig. 11 — Estimated percentage of word articulation vs. (a) noise at the subscriber's telephone and (b) transmission loss.

Whether one uses articulation tests or the direct method described previously, each of the resulting equated transmission losses turns out to be invariant over a large range of received speech volume. This, of course, is an *a priori* requirement. In principle, the equated transmission loss for a given degrading effect must be independent of all others, if the sum of equated transmission losses for all effects is to be a meaningful figure of merit.

In assessing message circuit efficiency, it is useful to view equated transmission losses as transmission impairments. Consider the estimated per cent articulation data of Fig. 11. We showed, for example, that 40 dbrn of noise at the subscriber's telephone is equivalent to an approximate 9.0-db increase in transmission loss. Since this equivalence implies that 40 dbrn degrades transmission by 9.0 db, relative to transmission at maximum per cent articulation (i.e., articulation at low noise), the 9.0-db value actually constitutes the amount of *noise transmission impairment* (NTI) due to 40 dbrn of noise at the telephone. On this basis, the equated transmission losses derivable from Fig. 11 are plotted as

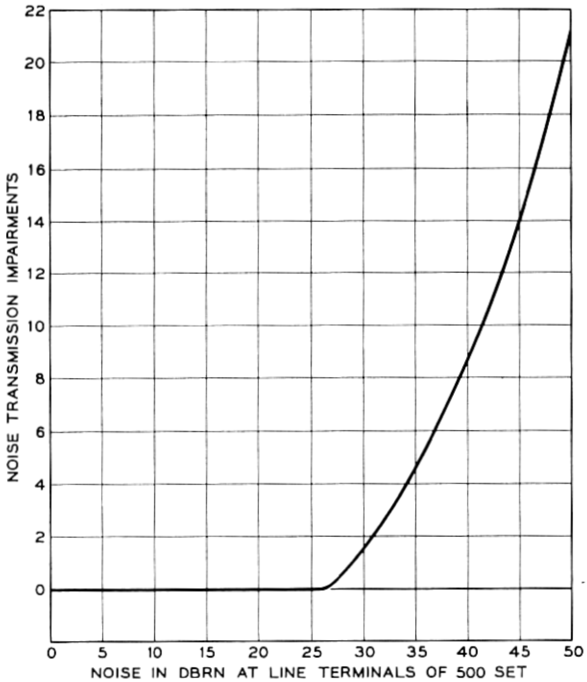

Fig. 12 — Estimated values of NTI from data of Fig. 11 under the zero NTI condition assumed in the text.

NTI versus noise in Fig. 12. For these data, a circuit with $\leqq$26 dbrn of noise at the line terminals would be said to suffer zero NTI; a circuit with a noise level of 30 dbrn would suffer an impairment of 1.5 db.

It is quite evident, however, that NTI by themselves will not indicate noise degradation on an absolute scale. For example, if the speech-to-noise ratio on a given circuit is large, say 35 db (in equivalent units), a 5-db NTI still leaves a good effective speech-to-noise ratio, (30 db), and the transmission is still good. On the other hand, if the speech-to-noise ratio is low, say 5 db, then a 5-db NTI will be nearly fatal to transmission. This does not mean that impairments are an inefficient measure, for the same is true of actual decibels. Increasing the transmission loss of two randomly chosen circuits by 5 db does not imply that they will be equal in performance, yet they have been degraded equally. Evaluation (of this type) in decibels, including effective decibels such as impairments, always requires consideration of the "initial conditions" of the circuit under study.

From the noise standpoint, we may summarize the above by saying that noise effects cannot be fully evaluated without giving regard to speech volume. Thus, in recent years emphasis has shifted toward the second type of assessment, which includes the effects of volume directly. Here the relationship expressing degradation differs from the db-impairment type of assessment, in that the effects of noise and volume are expressed directly in terms of telephone-user attitudes.

Expressions of attitude can be obtained in a number of ways. Experimentation has shown that the method of absolute judgment[14,15] tends to produce readily applicable results. The general nature of this method is as follows: first, the experimenter selects the range and levels of the stimuli to be evaluated. The various stimuli $S_\alpha (\alpha = 1, 2, \cdots, \nu)$ are then presented in random order to the observer, who is required to judge each condition in terms of one of a predefined set of response categories R_k $(k = 1, 2, \cdots, l)$. Specifically, the stimuli are joint "received speech volume-noise" conditions in the presence of average room noise to incorporate the three most important parameters that tend to affect transmission. While the response categories are arbitrary, it is the practice to use excellent, E; good, G; fair, F; poor, P; and unsatisfactory, U.

Each time a stimulus is presented, the outcome is a judgment in one of the l predefined response categories. Thus, if this procedure is repeated for a large number of observers, the relative frequency of occurrence of a category R_k, given S_α, will tend to approach the conditional probability $p(R_k \mid S_\alpha)$; i.e., the placement of a stimulus in category k given that the stimulus is at the level α. Note, since one and only one category is assigned by every observer to each S_α,

$$\sum_{k=1}^{l} p(R_k \mid S_\alpha) = 1.$$

In contrast to equated transmission losses for noise, the results in the above procedure are probabilities of the occurrence of certain expressions of attitude. Earlier, for example, we assumed an equated transmission loss of 1.5 db for 30 dbrn at the input of the 500 set. The 1.5-db value was then adjusted to provide a measure of noise degradation in terms of NTI. Under the method of absolute judgment, we would obtain the numerical values of $p(R_k \mid S_\alpha)$ for each level of received speech volume with noise at 30 dbrn. For y vu, one might find a value of 0.2 in the E category, 0.5 in the G category, 0.2 in the F category and 0.1 in the P category. In terms of the proportion of observers responding, these numbers tend to indicate an expectancy of subscriber satisfaction — a feature not reflected directly in impairments. For example, suppose we conduct a joint noise level-received speech volume survey in a particular community, say in locale A. Then for the joint distribution we could use either a table of noise and volume-loss impairments to determine the proportion of calls that are x db "poorer" than the reference-zero impaired call, or we could use the results of a joint noise-volume absolute judgment test to determine the proportion of calls that will be considered E, G, F, P and U. While the use of impairments gives the proportion of calls with specified values of over-all degradation, there is no direct measure of the over-all grade of transmission. Use of categorical judgments, on the other hand, provides some insight into this important question.

To illustrate the use of absolute judgments as implied above, let us assume that we have completed an absolute appraisal of joint volume-noise conditions $S_\alpha = (v_i, n_j)$, where α ranges over all combinations of volume v_i at level $i = 1, 2, \cdots, n$ and noise n_j at levels $j = 1, 2, \cdots, m$; and that S_α covers the range of any distribution of calls $p(S_\alpha) = p(v_i, n_j)$ in locale A.

Consider now any subscriber in A. In terms of the absolute judgment test, the event R_k for this subscriber is the placement of a randomly presented call in category k.* Due to the nature of R_k this event is dependent on the occurrence of some S_α. Since any S_α can occur, the event R_k occurs either as the result of both R_k and S_{11}, or both R_k and S_{12}, $\cdots$, or R_k and S_{nm}.

Symbolically, this means that

$$R_k = R_kS_{11} + R_kS_{12} + \cdots + R_kS_{nm}$$

and, since the joint events R_kS_α are mutually exclusive, their probabilities add. Thus,

$$\begin{aligned} p(R_k) &= p(R_kS_{11}) + p(R_kS_{12}) + \cdots + p(R_kS_{nm}) \\ &= p(R_k \mid S_{11})p(S_{11}) + p(R_k \mid S_{12})p(S_{12}) + \cdots \\ &\qquad + p(R_k \mid S_{nm})p(S_{nm}) \\ &= \sum_\alpha p(R_k \mid S_\alpha)p(S_\alpha), \end{aligned}$$

where $p(R_k)$ is the probability that a random call S_α of joint volume-noise (v_i, n_i) is placed in category k.

If $p(R_k)$ is interpreted in the frequency sense, it gives the proportion of calls placed in category k for the given set S_α. In these terms, $p(R_k)$ is called the "grade of service"[16] for the distribution $p(S_\alpha)$.

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* It is assumed here than an S_α *selected* in the experiment will be judged in the same category as the S_α appearing *randomly* at the subscribers telephone. More generally, the assumption implies that $p(R_k \mid S_\alpha)$ is stable.

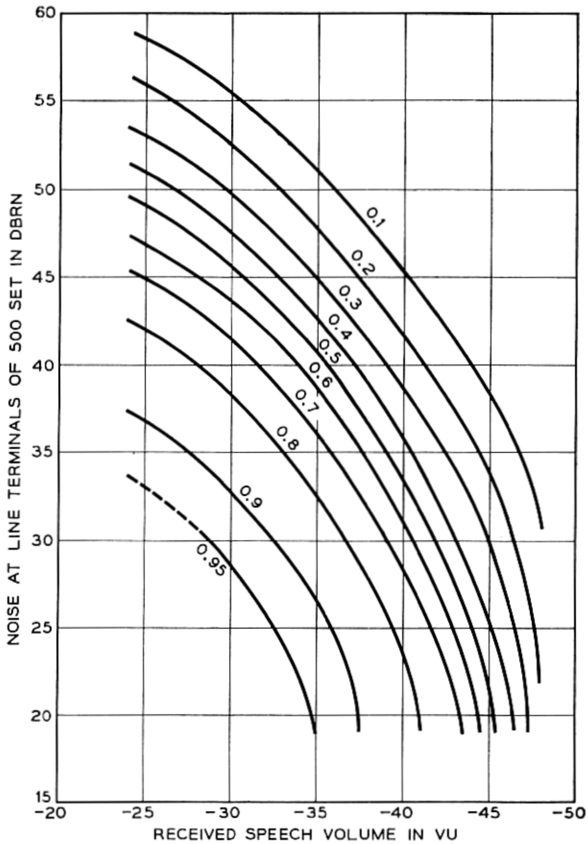

Fig. 13 — Absolute judgement: proportions of observers responding in the "good or better" category for the indicated joint volume-noise conditions.

In the more general case, where the joint volume-noise conditions S are distributed continuously with density $p(S)$, and when it is possible to obtain a continuous function $p(R_k \mid S)$ to represent $p(R_k \mid S_\alpha)$ for all α, grade of service is given by

$$\int_S p(R_k \mid S)p(S)\, dS,$$

where $S = (v,n)$.

As an example, Fig. 13 shows a part of the results of a joint volume-noise appraisal test: namely, the sum of E + G responses. Here, the conditional probabilities are of the form

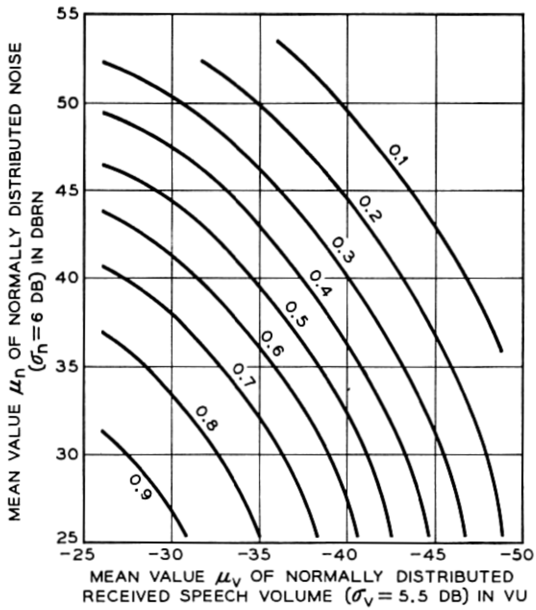

Fig. 14 — Grade of service estimates: proportions of "connections" in a bivariate normal noise-volume distribution (σ_n = 6 db, σ_v = 5.5 db) assignable to the "good or better" category when the means μ_n and μ_v have the indicated values.

$$p\left(\sum_{k=1}^{2} R_k \mid v,n\right) = p(\mathrm{E} + \mathrm{G} \mid v,n),$$

giving the probability that a volume-noise condition (v,n) is judged either excellent or good, i.e., "good or better". While such tests must be conducted at discrete levels, the incremental changes in this case were small enough to justify smoothing the data into a continuous form so that any response could be read. For simplicity, we have shown only a limited number of conditional probabilities. Notice that they are approximated by a set of contours that define equal proportions of "good or better" response in the speech volume-noise level plane. By fitting a polynomial $w(v,n)$ to these contours, the expression for "good or better" volume-noise grade of service becomes

$$\int_v \int_n w(v,n)p(v,n)\ dv\ dn.$$

An illustration of the applicability of the above is presented in Fig. 14. For $p(v,n)$ we have assumed an ensemble of bivariate normal distributions wherein v and n are assumed to be independent. The standard deviations were assumed to be fixed at $\sigma_v = 5.5$ db and $\sigma_n = 6$ db, whereas the means were allowed to vary continuously over the limited range of received volume (vu) and noise level (dbrn) as shown.*

The use of a continuous set of distributions is fully appropriate. While the grade-of-service integral becomes a function of μ_v and μ_n, it may readily be approximated by a finite double sum suitable for solution by means of digital computation. Furthermore, a solution in terms of the two means gives a bird's-eye view of the rate of change of grade of service, and it also exhibits the element of "tradability" between received speech volume and noise level on a macroscopic scale.

For simplicity, the "good or better" grade of service estimates in Fig. 14 are shown at the same numerical proportions as the conditional probabilities of Fig. 13. Here, however the contours define subjectively equivalent distributions at various levels of "goodness". Thus, for the particular choice of standard deviations, a joint volume noise distribution with $\mu_v = -34$ vu and $\mu_n = 27.4$ dbrn is seen to be subjectively equivalent to one with $\mu_v = -28$ vu and $\mu_n = 35.3$ dbrn.

In a similar but conceptually different way, one could also find subjectively equivalent volume-noise distributions from the point of view of impairments. The two cited above would not necessarily be equivalent, but, if we assume that they are, the outcome would be a table relating various proportions of these distributions to their respective impairments. As was said earlier, however, these proportions do not convey the same feeling of customer reaction as do the grade-of-service proportions. For the two joint distributions under discussion, one can expect that 80 per cent of the calls will be "good or better" — a language that has considerable appeal.

VI. ACKNOWLEDGMENTS

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* Actually the integration is defined only over the surface $w(v,n)$. Thus, there is some error incurred for distribution with low and high values of mean μ_n, μ_v near the periphery of the surface.

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