A System of Effective Transmission Data for Rating Telephone Circuits

By F. W. McKOWN and J. W. EMLING

A previous paper[1] introduced the idea of rating the transmission performance of telephone circuits on the basis of repetition observations and outlined briefly a method for expressing such ratings. The present paper describes in some detail a system for presenting these data in a form suitable for engineering use and the steps required for obtaining these data from the repetition observations.

INTRODUCTION

A TELEPHONE circuit may be described in terms of its physical characteristics, but these characteristics do not in themselves indicate the transmission results which will be obtained by its users in service. Laboratory talking tests, such as articulation tests,[2] indicate the ability of the circuit to transmit speech sounds under the conditions of the tests. In service, however, a wide and complex range of conditions is encountered and in the case of a new kind of instrument or circuit the service conditions may be modified in an unpredictable way due to the users' reactions. The complexity and a priori uncertainty of these conditions point to the advantage of ratings obtained during actual service.

The real criterion for rating a circuit is its transmission performance when in actual use as a link in the extremely complicated and variable communication channel between the brain of one telephone user and the brain of another telephone user. The paper by Mr. Martin[1] fully developed this idea and described a quantitative method for providing ratings on this basis of the transmission performance of a circuit, which method includes the effects of such circuit characteristics as volume loss, noise, distortion and sidetone. This method uses as a measure of circuit performance the number of repetitions requested by normal telephone users per unit time while using the circuits in actual service, on the basis that this number is a direct quantitative measure of the success with which telephone users carry on conversations. The previous paper also discussed other methods of rating the transmission performance of telephone circuits such as articulation

---

[1] "Rating the Transmission Performance of Telephone Circuits," W. H. Martin, *B. S. T. J.*, Vol. X, p. 116.

[2] "Articulation Testing Methods," H. Fletcher and J. C. Steinberg, *B. S. T. J.*, Vol. VIII, p. 806. "Developments in the Application of Articulation Testing," T. G. Castner and C. W. Carter, Jr., this issue of the *B. S. T. J.*

tests, volume tests and judgment tests and their relation to the repetition method.

The present paper describes the development of this rating method into a system of data for exchange area circuits which gives a convenient means of determining from the physical makeup of a complete telephone circuit a rating of the effectiveness of the transmission between normal subscribers using the circuit. Such data are called *effective* transmission data to distinguish them from previous transmission data which were based largely on volume losses. The effective data are expressed in terms of the db of effective loss relative to a reference circuit. An effective loss of 1 db is introduced into the reference circuit when the loss of the trunk is increased by 1 db at all frequencies without other change. Any other change in the circuit which has the same effect on its transmission performance as this distortionless change in volume loss also causes an effective loss of 1 db. The equality of performance is judged by the equality of repetition rates.

The problem of converting repetition data obtained from a relatively small number of circuits into usable transmission ratings for the very large number of practical circuit combinations resolves itself into two major parts: first, a choice of the form in which the data should be presented for use in laying out the telephone plant, and second, the actual preparation of the numerical data.

The preferable form for presenting the data is fixed by the nature of telephone exchange service. The general transmission problem is not to design a complete telephone circuit from one particular station to another particular station, but rather to design each circuit element separately in such a way that any complete circuit made up of these elements will give satisfactory transmission. Thus, each element, such as a subscriber loop or an interoffice trunk, must be designed to work as a part of any one of a large number of different connections. The technique for solving this problem on the basis of volume losses was worked out long ago in a satisfactory way and has been in use for many years. Volume loss data were prepared in convenient form for all available types of circuit elements, with the losses of the elements defined in such a way that when all the component losses were added the loss of the complete connection was obtained. These component volume losses were based, in general, on voice-ear tests or computations showing the effect on the volume of the received sound, of inserting the element to be rated in a reference system. With data set up in this way, it was possible to apportion the permissible overall rating between the different types of circuit elements and then to choose the facilities for each individual element separately so that its loss would not exceed the permissible loss. In a particular area, for example, the transmitting loss of each loop might be limited to 8 db or less, the receiving loss to 3 db or less, the total office losses on a connection to 1 db or less and the losses of an interoffice trunk to 6 db or less. In this case, no interoffice connection would have a loss of over 18 db regardless of which stations in the area were involved. This method makes it possible to design the circuit elements separately and also simplifies the presentation of data for the very large number of combinations of facilities available for the telephone plant.

A method has been developed for assigning effective loss ratings to parts of a circuit and presenting them in a form very similar to that used for the volume loss data. The advantages of this form are retained, therefore, even though the data include the effects of distortion, sidetone and noise in addition to volume losses.

The second problem, the preparation of numerical transmission rating data for the various types of facilities available for use in the telephone plant, requires a somewhat indirect attack because of the large amount of data required. Theoretically it would be possible to obtain relative effective ratings directly by means of repetition counts for all the circuit and instrument combinations which might be of interest in plant design. These ratings of complete circuits could then be broken down into ratings for the individual circuit elements. This method of attack, however, is entirely impractical because there is an almost infinite number of combinations of circuit elements and it would take some weeks of observation time on each combination. It is necessary, therefore, to make observations on a relatively small number of circuits chosen to cover the whole range of conditions and to obtain ratings for other circuits by interpolation between the ratings which have been obtained directly.

The method of interpolating which has been found practicable is based on the fact that the performance of a complete circuit can be described, with sufficient accuracy for most engineering work, as a function of the characteristics, volume loss, sidetone, distortion and noise. The magnitude of all of these characteristics, for any circuit using conventional types of instruments, can be derived from physical measurements. Since this can be done for each of the circuits used in the repetition tests, relations can be obtained for converting changes in noise, sidetone, or distortion into equivalent distortionless changes in volume loss. For any other complete circuit, it is necessary only to determine the magnitude of these characteristics by measurements and computations, and to convert them to effective ratings by means of the relations. These ratings of complete circuits can then be divided up into ratings of individual circuit elements.

FORM OF EFFECTIVE DATA

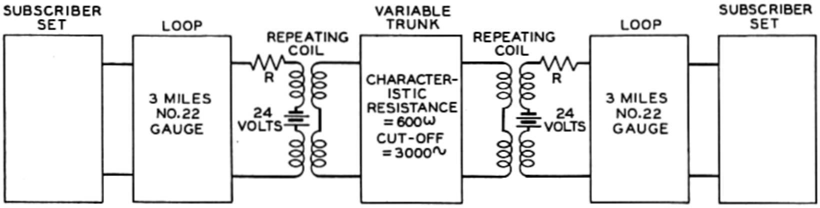
As stated before, the purpose of the effective data is to give a means of computing a transmission performance rating of a complete telephone circuit from the physical makeup of the circuit. These ratings, which are called effective transmission equivalents, are based on the definition that two complete circuits have the same effective transmission equivalent when under the same conditions of use they give the same grade of service as indicated by the repetition rate. The term *complete circuit* as used here includes the transmitter and receiver as well as the other elements of the electrical circuit. Circuit noise is, of course, one of the characteristics of a circuit and room noise may be treated as if it were a circuit characteristic, since it affects the transmission results obtained by the users of the circuit.

Reference System

In addition to adopting a criterion for the equality of two circuits, it is necessary to adopt a scale for the rating of circuits which differ in performance over a wide range. This has been done by a method analogous to that used for expressing volume equivalents. A reference circuit has been selected, to which a rating has been assigned as discussed below. This reference system may be varied from its normal adjustment by distortionless changes in the loss of the trunk, which forms a part of the system, until the reference system is equal in performance to the circuit being rated. Each change of 1 db in this trunk by definition changes the effective equivalent of the reference system by 1 db. Thus, the effective equivalent of circuits may be determined by comparison with the reference system.

The requirements of a reference system for effective transmission equivalents are: (1) that it be reproducible from simple physical measurements, and (2) that its performance can be compared with the performance of the circuits to be rated. Theoretically these are the two requirements for the reference system if it is to be used simply for rating complete circuits. As discussed later, since the system is to be used for determining effective losses of circuit elements as well as effective equivalents of complete circuits, there is the additional requirement (3) that it have characteristics similar to the commercial circuits to be rated. No system is available at present which fully meets all three requirements or even the first two, since present systems meeting requirement (1) are essentially laboratory devices and cannot be compared with other circuits under typical operating conditions. In order to meet the last two requirements, it has been necessary to adopt for the present a working reference system which is described in terms of particular instrumentalities instead of in terms of physical measurements. As plant conditions change other working reference systems may be required. If any other reference system is adopted it may be rated in terms of the existing working reference system, in which case the overall rating of any complete circuit which can be rated in terms of both systems will be approximately the same in terms of either reference system.

The working reference system which has been adopted is shown schematically in Fig. 1. It consists of two representative subscriber



R=25ω DC AS AN ALLOWANCE FOR RELAY, OFFICE WIRING AND HEAT COILS

LINE NOISE=100 NOISE UNITS IN RECEIVER
"TYPICAL" ROOM NOISE AS SHOWN IN FIGURE 2

Fig. 1—Working reference system for the specification of effective losses.

sets on three-mile 22-gauge cable loops connected, through repeating coils supplying 24-volt talking battery, to a trunk having a pure resistance characteristic impedance and an adjustable attenuation. The present working reference trunk has a very high attenuation above 3000 cycles to simulate loaded lines. Below this frequency the attenuation is independent of frequency and can be varied distortionlessly so that differences in effective ratings can be expressed in terms of differences in trunk attenuation. It has a 600-ohm characteristic impedance. The circuit noise in the receiver of the working reference system is 100 noise units. The room noise associated with this reference system is that distribution of noise which normally will be found in relatively quiet offices and in relatively noisy residences. The average magnitude of noise in such locations relative to other familiar conditions is shown by Fig. 2.

Any convenient rating may be assigned to the working reference system. The Standard Cable Reference System with a trunk of zero length, which was used for specifying volume losses, was the best circuit commercially available at the time it was adopted and was given a rating of zero. This reference point was continued essentially unchanged long after the time when this significance of the zero had been lost by the introduction of improved facilities, and after the Standard Reference System was replaced by the Master Reference System.[3] Because of the long use of this reference point both for rating circuits and for specifying standards of transmission, the numerical values of the volume equivalents of the circuit and the volume losses of the component parts, expressed by this system, have become associated with transmission performance and it is considered desirable, at least for the present, to retain this significance of the numbers as far as possible with the new method of describing circuit characteristics. This has been accomplished, first, by selecting typical limiting conditions for the working reference system and, second, by making the effective equivalent of this system numerically equal to the volume equivalent obtained from the volume loss data. This numerical equality holds for the working reference system with any adjustment of the line provided that the trunk contains enough attenuation to prevent material effects due to the interaction between the

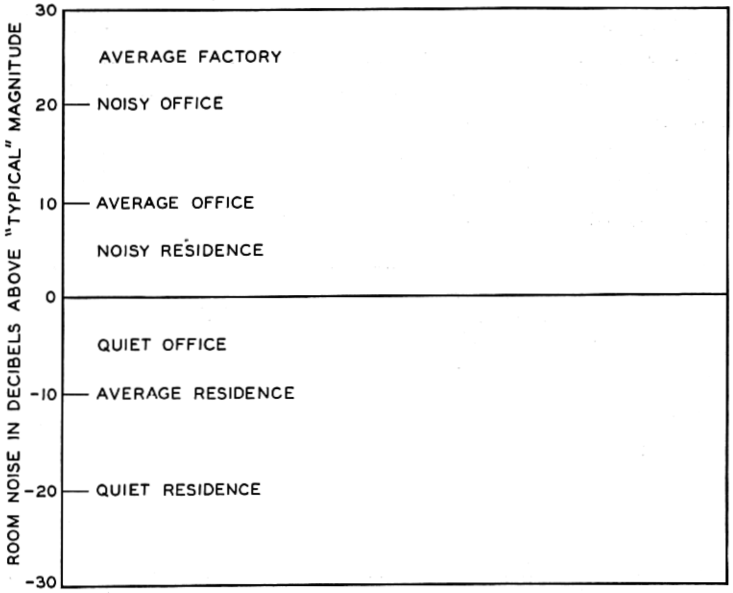


Fig. 2—Room noise in familiar locations relative to typical magnitude.

---

[3] "The Transmission Unit and Telephone Transmission Reference System," W. H. Martin, *B. S. T. J.*, Vol. III, p. 400. "Master Reference System for Telephone Transmission," W. H. Martin and C. H. G. Gray, *B. S. T. J.*, Vol. VIII, p. 536.

terminals. The normal adjustment is that for which the working reference system has an 18 db volume equivalent. The effective equivalent of any other complete telephone circuit is also equal to 18 db if it provides the same grade of service as the normal adjustment of the working reference system.

Ratings for Circuit Elements

The division of the effective equivalent of a complete circuit into its various parts, which are called effective losses, could be done in any one of several ways. The procedure described below appears to be the most suitable considering convenience, significance of the losses assigned to each element, and consistency with the form of previous transmission data.

The individual effective losses which in general make up the effective equivalent of a complete circuit include the following:

1. Transmitting loop loss.
2. Receiving loop loss.
3. Trunk loss.
4. Terminal junction loss.
5. Central office loss.
6. Intermediate junction loss.
7. Circuit noise loss.
8. Room noise loss.

The apportionment of the total normal rating of 18 db among the parts of the reference system can be done in any way which is convenient. The performance significance of the numerical values assigned by the volume loss method of rating has been retained by making the effective ratings of the working reference trunk and transmitting and receiving loops equal to those obtained from the previous volume loss data.

The loop losses are ratings of a subscriber station, subscriber loop, and a basic central office circuit. They are determined by comparison with the corresponding element of the working reference system, in each case using the remaining elements of the working reference system to complete the circuit and using the same electrical circuit noise and the same room noise as specified for the reference system. For example, any transmitting loop, which is substituted for the reference transmitting loop and which gives the same grade of service, also has an effective loss equal to the loss of the reference loop. Any loop which gives service effectively X db better has an effective loss equal to the assigned loss of the reference loop minus X db, and any loop which gives service Y db poorer has a loss of Y db more than the loss of the reference loop. Receiving loops are rated relative to the reference receiving loop in the same way, the difference in effective loss of the two conditions being subtracted from or added to the assigned effective loss of the reference receiving loop. These losses are given in curve form, similar to Fig. 3. They include the effects of variation in sidetone and distortion with loop length as well as the variation in volume loss. In some cases the loss on extremely short loops is greater than on loops of intermediate length because of the rapid increase in sidetone with decrease in loop length.

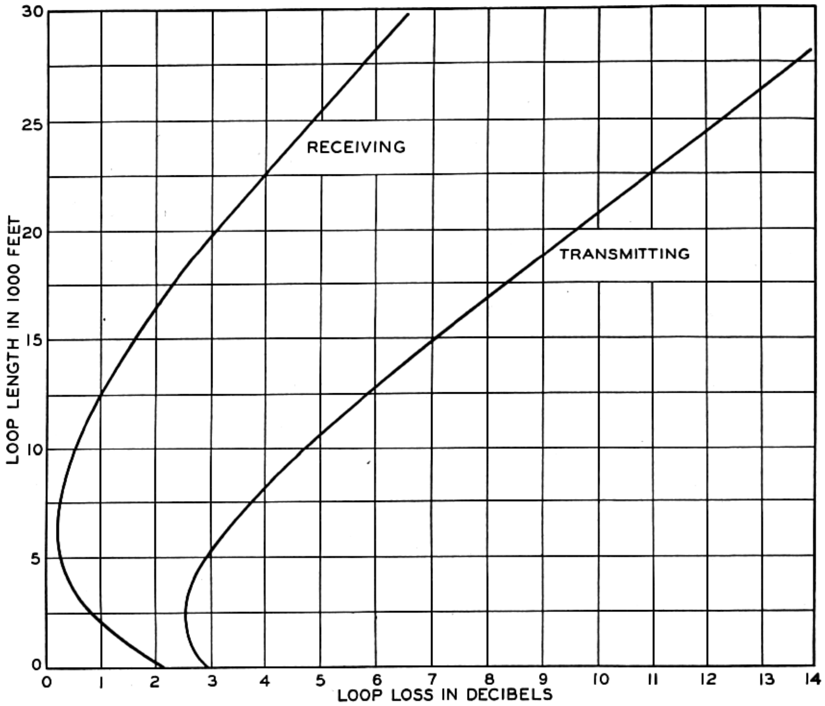


Fig. 3—Effective loop losses.

The effective loss due to substituting any type of trunk for the reference trunk in the reference system could be determined and the loss data for various lengths presented in curve form in the same way that effective loop losses are presented, but the same curve would not apply for the loss of this type of trunk between other than the reference loops. If two or more such curves, as shown in Fig. 4, are determined for a particular type of trunk when used with different loops, two important facts are evident: (1) the curves are practically straight over the more important range (solid lines in Fig. 4), and (2) the straight parts of the curves are practically parallel. For trunks which are electrically short the straight line relation does not hold, but in most cases the exact loss of such short trunks is relatively unimportant. It is possible, therefore, to describe the loss of a particular type of trunk over a wide range of conditions in terms of a series of linear equations all having the same slope but with intercepts which depend

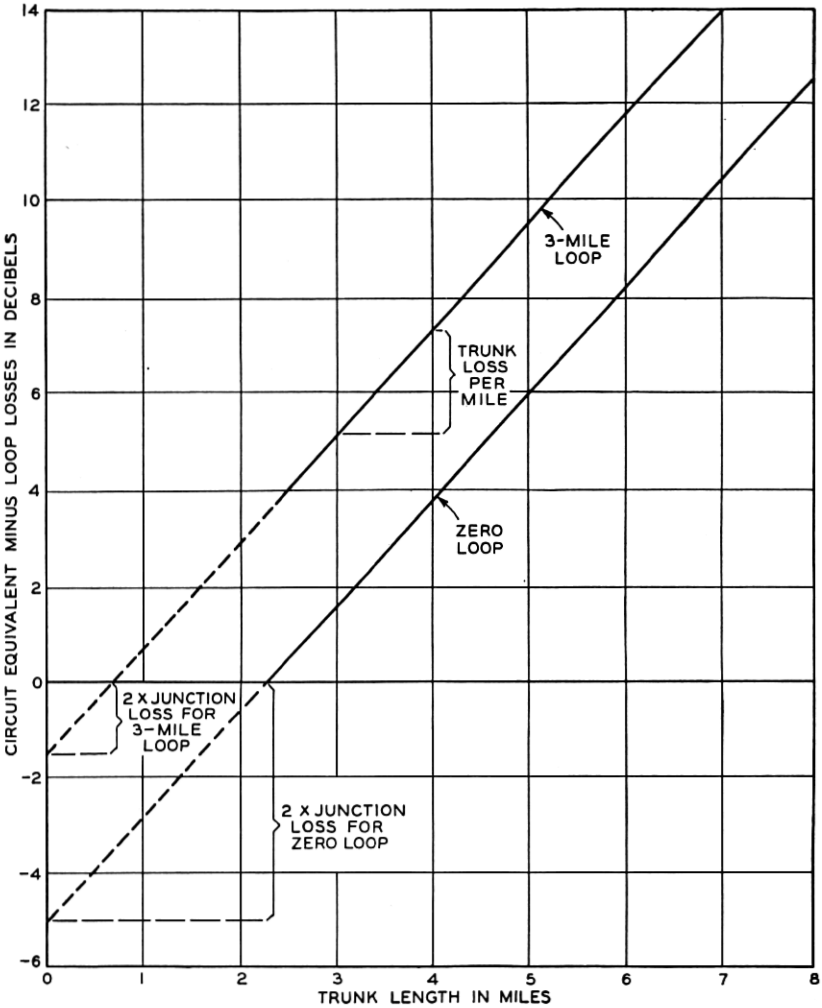


Fig. 4—Effective trunk and terminal junction losses.

on the type and length of the subscriber loop. This is exactly the method used in the volume data where its use followed logically from the mathematics which give the loss of a line at a single frequency. The use of this method with effective data is permissible only because the effects of trunk distortion as well as volume loss can be treated, with a satisfactory degree of approximation, as a linear function.

The trunk loss per unit length equals the slope of the curves and can be defined, therefore, as the increase in effective loss per mile increase in length of a trunk, which is initially electrically long, when used between the reference loops. In the case of loaded trunks, this increase in length must be accomplished without change in end section. The trunk loss per unit length, although measured between the reference loops, can be treated as independent of loop. It includes two component losses, the volume loss per unit length, and the effect of the increase in distortion per unit length.

Effective terminal junction losses are corrections associated with the junction of a loop and trunk which are added in computing the effective equivalent of a circuit employing a trunk other than the reference trunk. For a circuit with two equal loops each loss equals one-half the Y intercept in Fig. 4. It is dependent on the type of set, the type and length of loop and on the type of trunk but is independent of trunk length. It contains a volume reflection correction, the effects of that part of the trunk distortion which is independent of length, and the effects of trunk impedance on sidetone. Fig. 5 is a sample of the form in which these losses are presented.

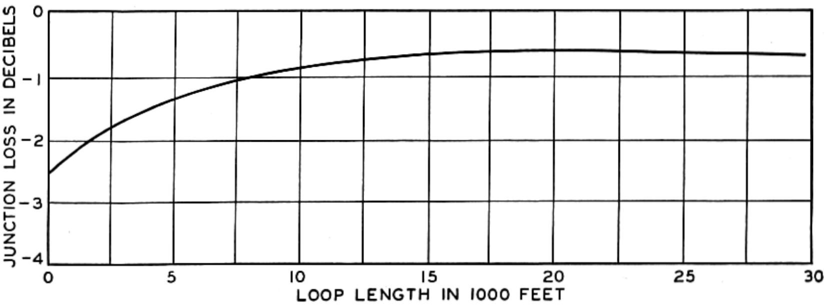


Fig. 5—Effective terminal junction loss.

The central office losses present data relative to the loss of central office apparatus and cabling other than that included in the loop losses. They are determined by substituting the apparatus to be rated for the corresponding parts of the working reference system, and equal the effective loss of this condition relative to the working reference condition. Somewhat different losses would be obtained with other loops and trunks, but the values obtained under the reference conditions give sufficiently good approximations for practical purposes.

The intermediate junction losses are corrections to be added to the other elementary losses when the trunk is made up of more than one type of facility. They include the volume reflection loss at the junction of the two facilities and a distortion correction which together with the other distortion losses of the elements will give a total equal to the distortion rating of the complete circuit relative to the reference.

The data covering the six types of losses discussed above are set up on the basis of the same electrical line noise and the same room noise as those specified for the working reference circuit.

Effective losses due to circuit noise may be presented in the form of curves showing the loss due to any amount of circuit noise. These losses are added to the other effective losses when the noise at the receiving loop terminal differs from the noise on the reference circuit. The amount of circuit noise on a particular circuit cannot usually be predicted accurately from the design constants of the circuit, since it depends largely on the characteristics of the disturbing circuits, the coupling between disturbing and disturbed circuits, and characteristics of the disturbed circuit which include random unbalances. Effective losses due to circuit noise, therefore, must, in general, be based on noise measurements rather than on the design constants of the telephone circuits.

Effective losses due to room noise may be added to the other effective losses when the room noise at the receiving end differs from the room noise associated with the reference system. Since the magnitude of the room noise at a particular station is in no way a function of the design of the telephone circuit this type of loss is in a somewhat different class from the others. More than one curve is required for presenting room noise loss since the loss depends to some extent on the sidetone of the telephone set.

The determination of a circuit rating from effective loss data is simpler than may appear from the description of the data. Exchange area circuits involve at most eight types of losses and most of these circuits involve a smaller number. Three of these losses, the transmitting and receiving loop losses and the terminal junction losses, are determined from curves similar to Figs. 3 and 5. The remaining losses, that is, the trunk, office, intermediate junction and noise losses, are obtained from simple tables or curves.

The definitions of losses have been set up so that the rating of an element is obtained when the element is substituted for the corresponding element in the working reference system, that is, when it is part of a typical telephone system. This method of determining losses was adopted because the effects of distortion, noise and sidetone in any one element depend to a greater or less extent on all the characteristics of the remainder of the circuit. It is therefore essential that each element of the reference system be fairly representative of the corresponding component of the telephone plant, if the ratings are to be approximately additive. This has been taken into account in the choice of the working reference system. Certain approximations are involved in the system of data outlined, but they are minor and are justified in the interest of simplification of the method.

PREPARATION OF EFFECTIVE DATA

Data for preparing effective loss ratings have been obtained primarily from repetition counts made during a series of special transmission observations on calls between telephone employees in the regular course of their business. These calls were made over special facilities which permitted the variation of the circuit constants over a wide range and the rating of the various conditions relative to each other in terms of repetitions. During these tests, different types of instruments were used and changes were made in the sidetone characteristics of the sets, and the attenuation and type of trunk. Each type of change covered rather completely the whole range found in the present telephone plant and to some extent that expected in the future plant, but it has been practicable to cover only a small portion of the combinations of instruments and circuits which might be used together in commercial service.

In the preparation of the necessarily large quantities of effective transmission data from the transmission observations, the principal problem is to determine the rating of any complete circuit from the limited number of complete circuits which have been rated directly. The determination of these additional ratings is relatively easy if the circuits can be described in terms of a few simple characteristics which will serve as a basis for interpolating between the ratings obtained directly from observations. The physical measurements which can readily be made in the required quantity describe a circuit in a complex manner, namely, in terms of the efficiency, at each frequency in the voice range, of the several speech and noise transmission paths of the complete circuit. These data must, therefore, be combined in some way to give a relatively small number of parameters for describing the circuit.

The definitions of these parameters may be more or less arbitrary, provided that the circuit performance is the same for circuits having numerically equal parameters regardless of differences in physical characteristics. The number of parameters required to describe a circuit is largely a matter of convenience. A small number tends to make the interpolation simple, but the derivation from the measurements complex. The converse holds for a large number. For preparing effective transmission data for the local plant, the circuit description has been expressed in terms of five parameters as follows: the volume loss from the transmitter of one set to the receiver of the other, the sidetone volume loss at the talking end, the sidetone volume loss at the listening end, the circuit noise efficiency of the station at the listening end, and the distortion. An important advantage of using these particular parameters is that each represents a circuit characteristic generally recognized as affecting transmission performance. The electrical line noise at the station end of each subscriber loop and the average room noise at the station are, of course, two other parameters which are maintained at the reference value except when computing line noise and room noise losses.

The computation of effective ratings from repetition observations and circuit measurements may be summarized as follows: The transmission observations are preferably made on various series of circuits, in each of which one parameter is varied while the others are kept constant. First, a series of observations is made on circuits which are identical except that the volume loss is varied by distortionless changes in the trunk attenuation; preferably these should be various adjustments of the working reference system. A second series of observations is made with a constant volume loss but with variations in some one of the other parameters; for example, the sidetone at one end of the circuit might be varied. From this series of tests in conjunction with the first series, the distortionless change in volume loss, which is equivalent to each change in sidetone, is determined both for transmitting and receiving and curves of effective loss versus sidetone may be established. Such curves are shown in Fig. 6. These effective losses apply only for this particular volume loss, but tests with other constant volume losses give essentially the same relations. The change in effective transmitting efficiency is due to the fact that telephone users raise their talking volume when the sidetone is reduced. The change in effective receiving efficiency is due to the fact that a reduction in sidetone reduces the interfering effect of room noise.

In the same way, distortion and noise are varied separately and the effect of each of these changes in terms of equivalent change in volume loss is determined.

Room noise losses are difficult to determine with any degree of accuracy by observing on working circuits since it is impractical to introduce artificial room noise, and natural variations in room noise are, in general, accompanied by other variations affecting repetitions. Laboratory or theoretical methods of determining these losses are not satisfactory since, as room noise changes, the subscriber consciously or unconsciously tries to counteract the effect and such reactions cannot be studied satisfactorily under controlled laboratory conditions. Each method, however, helps to determine the general magnitude of these effects.

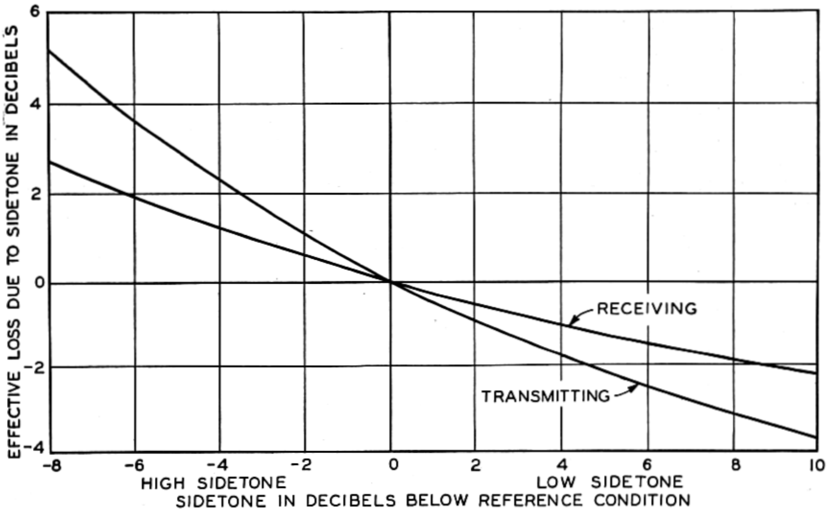


Fig. 6—Effective loss due to sidetone relative to working reference condition.

In practice it is seldom possible to vary one parameter over a wide range without causing some variation in the other parameters, but this does not add any serious complication to the derivation of the relations. It is merely necessary to make successive, approximate corrections when deriving each relation.

After these relations have been established, it is possible to predict the performance of any ordinary circuit by computing the five parameters from the physical measurements. The magnitude of each parameter may then be compared with the magnitude of the same parameter in the reference system, and the difference between the two magnitudes may be converted into equivalent distortionless changes in volume loss by means of the curves. These ratings may then be combined to give a single effective loss rating of the circuit.

For the normal range of conditions existing in the telephone plant simple algebraic addition of the component ratings gives the combined rating with sufficient accuracy provided the individual ratings are obtained under typical conditions. Ratings can be obtained only for complete circuits, since some of these parameters, such as distortion, have no meaning except when applied to a complete circuit, and others, such as sidetone, depend on two or more circuit elements. However, by choosing for computation complete circuits in which the elements to be rated are substituted for the corresponding element of the reference circuit, it is possible to determine the effective losses of individual circuit elements in accordance with the definitions given previously.

The parameters used for describing circuits have been used previously in a qualitative sense and several have quantitative definitions based on listening tests. A problem is presented, however, by the necessity for computing them from physical measurements. Volume loss, for example, has been defined in terms of voice-ear comparisons with an adjustable reference condition. Such a definition is satisfactory for describing this parameter but the testing method is cumbersome for obtaining the large amount of data required for engineering purposes. If, however, a series of such volume loss measurements is made on a large number of circuit conditions for which the physical characteristics are varied systematically, an empirical formula can be derived for weighting and combining the efficiencies measured over the voice-frequency range. Using this formula, the volume loss of other conditions can be readily computed. Similar methods may be used for deriving empirical formulas for computing noise and sidetone volume losses from the basic physical characteristics.

The use of distortion in a quantitative sense requires the adoption of a scale for this parameter. The only requirement for such a scale is that any two circuits having the same amount of distortion, all other parameters being equal, will give the same repetition rate. The term distortion factor is applied to the particular scale used in this work and its definition is derived from laboratory articulation tests. These tests are made on a large number of circuits which have equal volume losses but which differ from each other in frequency characteristics. The empirical formula for computing the distortion factor from the basic circuit measurements is set up so that all of the circuits which give the same articulation rate will have the same distortion factor. From service observations made on a number of different types of circuits it has been shown that, with all other parameters constant, circuits having the same distortion factor will give essentially the same repetition rate. Presumably, other scales for expressing distortion could be used, with other formulas, and possibly these can be derived directly from repetition observations if a great enough variety of circuits is covered. In any case, it appears that some such distortion factor is needed since distortion in any complete telephone connection is too complicated to be classified by any simple means, such as specifying a cutoff frequency.

It should be pointed out again that the computations and measurements described provide merely a means of interpolating between transmission observation results and have both the limitations and advantages of an interpolation method. They cannot be used to predict performance of any circuit radically different from those covered by repetition counts, but on the other hand, any inaccuracy in the formulas used in computing the parameters is of only secondary importance since they are used only for interpolating between observed points. For limited applications to simpler circuits more direct methods might be satisfactory. For more complicated circuits, such as present-day long toll circuits, other parameters are needed to describe such characteristics as delay distortion and echoes.

Conclusion

The effective transmission data can be applied in practically the same manner as the volume loss data which they replace. Consequently, the effects on transmission service of distortion, noise and sidetone, as well as of volume loss, can all be taken into account in the design of the plant in a simple, systematic way. Such comprehensive transmission ratings are required to utilize properly the various types of facilities now employed in the telephone plant, to direct future developments, such as further reductions in distortion, and to incorporate into the plant the new types of facilities resulting from these developments.