The Transmission Unit and Telephone Transmission Reference Systems[1]

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SYNOPSIS: Consideration is given to the method of determining and expressing the transmission efficiencies of telephone circuits and apparatus, and of the desirable qualifications for a unit in which to express these efficiencies. The "transmission unit" described in this paper has been selected as being much more suitable for this purpose under present conditions than the "mile of standard cable" which has been generally used in the past.

THE "mile of standard cable" has been used in telephone engineering in this country for over twenty years, and during that time has been adopted in other countries, as the unit for expressing the transmission efficiency of telephone circuits and apparatus. In the present state of the telephone art, this unit has been found, however, to be not entirely suitable and it has recently been replaced in the Bell System by another unit which for the present, at least, has been called simply the "transmission unit." Before considering the reasons for such a fundamental change and the relative merits of the two units, it may be well to review briefly the general method of determining the efficiency of such circuits and the apparatus associated with them.

The function of a telephone circuit is to reproduce at one terminal the speech sounds which are impressed upon it at the other terminal. The input and output of the circuit are in the form of sound and its efficiency as a transmission system may be expressed as the ratio of the sound power output to the sound power input. For commercial circuits, this ratio may be of the order of 0.01 to 0.001.

In the operation of the system, the sound power input is converted by the transmitter into electrical power, which is transmitted over the line to the receiver and there reconverted into sound power. The effect of inserting a section of line or piece of apparatus or of making any change in the circuit can be determined in terms of the variation which it produces in the ratio of the sound power output to the sound power input, or, if this latter is kept constant, in terms of the ratio of sound power output after the change to that obtained before the change was made. It should be noted particularly that the change in the output power of the system is the real measure of the effect of any part of the circuit on the efficiency of the system and that the ratio of the power leaving any part to that entering it is not necessarily the measure of this effect. For example, a pure

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reactance placed in series between the transmitter and the line, may change the power delivered to the line by the transmitter and hence the output of the receiver, the magnitude and direction of the change being determined by the impedance relations at the point of insertion. The ratio of the power leaving the reactance to that entering it is, of course, unity, as no power is dissipated in a pure reactance. In other words, the transmission efficiency of any part of a circuit cannot be considered solely from the standpoint of the ratio of output to input power for that part, or the power dissipated in that part, but must be defined in terms of its effect on the ratio of output to input power for the whole system.

By determining the effect of separately inserting the many pieces of apparatus that may form parts of typical telephone circuits, an index can be established for each of these parts of its effect on the efficiency of the circuit for the conditions of which the circuit tested is typical. Similarly, the power dissipated in unit lengths of the various types of line can be determined by noting the change in power output of the receiver caused by increasing any line by a unit length. Such indices of the transmission efficiencies of the various parts of a circuit obviously have many applications in designing and engineering telephone circuits. These indices could be taken as the ratios expressing the change in the output power of the system. This, however, has certain disadvantages. For example, the combined effect of a number of parts would then be expressed as a product of a number of ratios. Likewise, for the case of a number of parts n of the same type in series, such as a line n miles in length, the effect would be expressed as the ratio for one part or one mile of the line, raised to the nth power. In many cases, these ratios and the powers to which they would need to be raised would be such as to make their handling cumbersome. If, however, these indices are expressed in terms of a logarithmic function of a ratio selected as a unit, the sum of any number of such indices for the parts of a circuit is the corresponding index for the power ratio giving the effect of the combination of these parts.

The "mile of standard cable" is such a logarithmic function of a power ratio. The new unit also meets this important requirement.

Definition of the Transmission Unit

The "transmission unit" (abbreviated *TU*) has been chosen so that two amounts of power differ by one transmission unit when they are in the ratio of $10^{0.1}$ and any two amounts of power differ by N units when they are in the ratio of $10^{N(0.1)}$. The number of transmission units corresponding to the ratio of any two powers P_1 and P_2, is then the common logarithm (logarithm to the base 10) of the ratio P_1/P_2, divided by 0.1. This may be written $N=10 \log_{10} P_1/P_2$. Since N is a logarithmic function of the power ratio, any two numbers of units, N_1 and N_2, corresponding respectively to two ratios, P_a/P_b

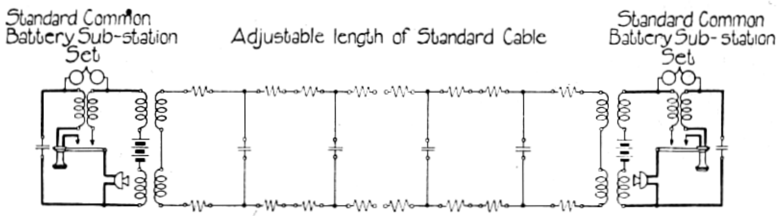

Fig. 1

and P_c/P_d, may be added and the result N_1+N_2, will correspond to the product of the ratios, $P_a/P_b \times P_c/P_d$.

From the above it is seen that the measure in transmission units of the ratio of two amounts of power P_1 and P_2 is N, where

$$N=\frac{\log \frac{P_1}{P_2}}{\log 10^{0.1}}.$$

In other words, the transmission unit is a logarithmic measure of power ratio and is numerically equal to log $10^{0.1}$.

The reasons for the selection of this unit and the method of applying it, can probably be best brought out by a consideration of the practise which has been followed in determining and expressing the efficiencies of telephone circuits and apparatus in terms of "miles of standard cable."

Standard Reference Circuit

Fig. 1 shows what has been designated the "standard reference circuit." It consists of two common battery telephone sets of the type standard in the Bell System at the time this circuit was adopted, connected through repeating coils or transformers to a variable length of "standard cable." This cable is an artificial line having a resistance of 88 ohms and a capacity of 0.054 microfarad per loop mile which is representative of the type of telephone cable then generally used in this country.

For a given loudness of speech sounds entering the transmitter at one end of the circuit, the loudness of the reproduced sounds given out by the receiver at the other end can be varied by changing the amount of standard cable in the circuit. Also, the amount of cable in the circuit can be used to express the ratio of the power of the reproduced sounds to that of the impressed sounds. Due to the dissipation of electrical power in the cable, this ratio and consequently the loudness of the reproduced sounds become less as the amount of cable is increased and greater as the length of cable is decreased.

This circuit then became the measuring or reference system for engineering the telephone plant and the "mile of standard cable" became the unit in which the measurements were expressed. This circuit was used to set the service standards in designing and laying out the telephone plant. Thus, the reproduction obtained over this circuit with a length of cable of about twenty miles was found suitable and practicable for local exchange, that is, intra-city service, and that corresponding to about thirty miles for toll or intercity service.

Any telephone circuit was rated by its comparison with the standard circuit. This comparison was on the basis of a speaker talking alternately over the circuit to be measured and the standard circuit and a listener switching similarly at the receiving ends, the amount of cable in the standard circuit being adjusted until the listener judged the volume of the sounds reproduced by the two systems to be equal. The number of miles of cable in the standard circuit was then used as the "transmission equivalent" of the circuit under test. The effect of any change in the circuit under test on the efficiency of that circuit could then be measured by determining the variation in the amount of standard cable required to make the sounds reproduced by the two systems again equal and the number of miles of standard cable required to compensate for this change was used as the index of this effect. In this way the relative efficiencies of two transmitters or receivers could be determined. Likewise, the power dissipation per unit length or the attenuation, of the trunk in the circuit under test could be equated to miles of standard cable. Since in each case, the standard cable is used to adjust the volume of the reproduced sound, "the mile of standard cable" corresponds to the ratio of two amounts of sound power, or as this change in sound power is produced by changing the power delivered to the telephone receiver, to a ratio of two amounts of electrical power.

If the addition of a mile of standard cable to a long trunk of the standard circuit causes the power reaching the end of the trunk to decrease by a ratio r, then the insertion of two miles will decrease the received power by a ratio of r^2 of that obtained before the two miles were inserted. A number of miles of cable, n, inserted will reduce the received power to a ratio r^n. Thus the power ratio corresponding to any given number of miles of cable is an exponential function of the ratio corresponding to one mile, the exponent being the length in miles. The length in miles is, therefore, a logarithmic function of the power ratio.

In an infinite length of uniform line having resistance, inductance, capacity and conductance of R, L, C and G per unit length, the attenuation a per unit length, of a current of frequency f flowing along the line can be shown to be equal to the real part of the expression

$$a+j\,b=\sqrt{(R+j\,2\,\pi f\,L)\,(G+j\,2\,\pi f\,C)}.$$

For the standard cable line, since L and G are zero

$$a=\sqrt{\pi f\,R\,C},$$

and since $R=88$ ohms and $C=0.054$ microfarad per mile the current attenuation per mile of standard cable is

$$a=0.00386\sqrt{f}.$$

If I_1' and I_2' are the currents, respectively, at the beginning and end of a mile of line, then

$$I_1'/I_2'=e^a \text{ or } a=\log_e I_1'/I_2'.$$

Similarly if I_1 and I_2 are the currents, at points 1 and 2, respectively, at the beginning and end of a section of l miles

$$I_1/I_2=e^{la} \text{ and } l\,a=\log_e I_1/I_2.$$

For this case, the effect of inserting the section of l miles into the line on the current at point 2, or at any point beyond 2, is that the currents at the point before and after the insertion are in the same ratio as I_1/I_2. Furthermore, since the impedance of the line looking toward the receiving end is the same at points 1 and 2 (and at any other points), then the ratio of the powers at the two points is equal to the square of the current ratio.

Thus the power attenuation is represented by

$$P_1/P_2=(I_1/I_2)^2=e^{2la}.$$

Similarly for a line, terminated in a fixed impedance which may be different from the characteristic impedance of the line, the ratio of the powers received before and after a change in the length of the line is equal to the square of the ratio of the corresponding currents. On the basis of this relation, and because it is in general more convenient to measure or compute currents than powers, the current ratio has often been used in determining the equivalent of any piece of apparatus or line in terms of standard cable. It should be noted, however, that such a current ratio can be properly used as an index of the transmission efficiency of a part of a circuit only when it is equal to the square root of the ratio of the corresponding powers. Also, of course, the voltage ratio can be similarly used when it meets the same requirement.

Limitations in Use of Standard Cable Unit

As has been shown above, the attenuation, either of current or power, corresponding to the mile of standard cable is directly proportional to the square root of the frequency of the current under consideration. This means that the standard cable mile corresponds not only to a certain volume change in the reproduced speech sounds, but also to a distortion change. For comparisons between the standard cable circuit and commercial circuits with talking tests and as long as most of the commercial circuits had distortion comparable to that of standard cable, this two-fold effect of standard cable was desirable. At present, however, many types of circuits are being used which have much less distortion than standard cable. Also, the use of voice testing has been largely given up in the plant and it is now the general practise to determine the efficiency of circuits and apparatus on the basis of measurements and computations for single-frequency currents, a correlation having been established between these latter results and those of voice tests. These factors have made it desirable to have a unit for expressing transmission efficiencies which is distortionless, that is, is not a function of frequency.

Qualifications of a New Unit

The consideration of a new unit for measuring transmission efficiency brought out the following desirable qualifications:

1. *Logarithmic in Character*. Some of the reasons for this have already been discussed. In addition, the application of such a unit in measurements of sound make a logarithmic unit desirable, since the sensation of loudness in the ear is a logarithmic function of the energy of the sound.

2. *Distortionless*. The advantages of a unit which is independent of frequency have been referred to above. In expressing the effi-

ciency of the transmission of the high frequencies involved in carrier and radio circuits, such a unit is particularly desirable.

3. *Based on Power Ratio.* This is desirable because the power ratio is the real measure of transmission efficiency. As pointed out above, the current ratio can be used only when it is equal to the square root of the power ratio. Having the unit based on a power ratio does not, of course, require that measurements or computations be made on a power basis.

In considering the conversions between sound and electrical energy, it is obviously advantageous to have a unit based directly on a power ratio.

4. *Based on Some Simple Relation.* This is desirable in connection with the matter of getting a unit which may be widely used and may find applications in several fields.

5. *Approximately Equal in Effect on Volume to a "Mile of Standard Cable."* One reason for this is the practical one of avoiding material changes in the conceptions which have been built up regarding the magnitude of such things as transmission service standards. Also, the sound power changes which can be detected by an ear are of the order of that corresponding to a mile of standard cable. In measuring telephone lines and apparatus with single-frequency currents, it has been found that an accuracy of about one-tenth of a mile can be obtained readily and is sufficient practically.

6. *Convenient for Computations.* This refers to the matter of changing from computed or measured current or power ratios to transmission units or vice versa.

Properties of the Transmission Unit

A consideration of the above qualifications and of the various units suggested, led to the adoption of the power ratio of $10^{0.1}$ as the most suitable ratio on which to base the unit of transmission efficiency. The transmission unit is logarithmic, distortionless, is based on a power ratio and its relation to that ratio is a simple one. Its effect on the transmission of telephonic power corresponding to speech sounds is about 6 per cent less than that of one mile of standard cable. Regarding its use in computations, it has the advantage that the number of units corresponding to any power ratio, or current ratio, can be determined from a table of common logarithms.

For a power ratio of 2, the logarithm is 0.301 and the corresponding number of units is, therefore, this logarithm multiplied by 10, which is 3.01 $T\ U$. For a power ratio of 0.5, the logarithm is $9.699-10=-0.301$ and the number of units is $-3.01\ T\ U$. A power ratio of 2 represents a gain of 3.01 units, and a power ratio of 0.5 corresponds to a loss of 3.01 units. If the above ratios were for current, the logarithms would be multiplied by 20. Thus a current ratio of 2 corresponds to a gain of 6.02 units and a current ratio of 0.5 corresponds to a loss of 6.02 units.

It will be noted that the *T U* is based on the same ratio $10^{0.1}$ as the series of preferred numbers which has been used in some European countries and has been proposed here as the basis for size standardization in manufactured articles.[2] In common with this series, the *T U* has the advantage that many of the whole numbers of units correspond approximately to easily remembered ratios as shown in the following table.

APPROXIMATE POWER RATIO

Transmission Units	For Losses		For Gains
	Fractional	Decimal	Decimal
1	4/5	0.8	1.25
2	2/3	0.63	1.6
3	1/2	0.5	2.
4	2/5	0.4	2.5
5	1/3	0.32	3.2
6	1/4	0.25	4.
7	1/5	0.2	5.
8	1/6	0.16	6.
9	1/8	0.125	8.
10	1/10	0.1	10.
20	1/100	0.01	100.
30	1/1000	0.001	1000.

It will be seen that the ratio for a gain of a given number of *T U* is the reciprocal of the ratio for a loss of the same number of units. Also for an increase of 3 in the number of units, the loss ratio is approximately halved and the gain ratio doubled. If the approximate loss ratios corresponding to 1, 2 and 3 units are remembered, the others can be easily obtained.

From this consideration of the properties of the transmission unit, it is evident that there is much to commend its use in telephone transmission work. Furthermore, since its advantages are not peculiar to this work, such a unit may find applications in other fields. It is now being used in some of the work on sound.

[2] Size Standardization by Preferred Numbers, C. F. Hirshfeld and C. H. Berry, *Mechanical Engineering*, December, 1922.

New Telephone Transmission Reference System

With the standardization of the distortionless unit of transmission it is desirable also to adopt for a transmission reference system a telephone circuit which will be distortionless from sound input to the transmitter to sound output from the receiver. This system will consist of three elements, a transmitter, a line and a receiver. Each will be designed to be practically distortionless and the operation of each will be capable of being defined in definite physical units so that it can be reproduced from these physical values. Thus the transmitter element will be specified in terms of the ratio, over the frequency range, of the electrical power output to the sound power input, this ratio being expressed in transmission units. The receiver element will be specified likewise in terms of the ratio of sound power output to electrical power input. The output impedance of the transmitter and the input impedance of the receiver elements will be 600 ohms resistance. The line will be distortionless with adjustments calibrated in transmission units and will have a characteristic impedance of 600 ohms resistance.

Such a reference system is now being constructed. The transmitter element consists of a condenser type transmitter and multistage vacuum tube amplifier. The receiver element consists of an amplifier and specially damped receiver. Each element is adjusted to give only negligible distortion over the frequency range.

It is proposed when this system is completed and adjusted that it will be adopted as the Transmission Reference System for telephone transmission work. Other secondary reference systems, employing commercial-type apparatus will be calibrated in terms of the primary system and used for field or laboratory tests when such commercial type systems are needed.