a survey of telephone transmission

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Pacific Telephone

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INTRODUCTION

People like to talk with each other. The Bell System is based on the belief that people want to talk to other people beyond the normal range of the human voice, and are willing to pay for the satisfaction of that want.

Any assembly of equipment which converts speech sounds to electrical waves, carries these electrical waves to a distant point, and uses them to create sounds which are substantially equivalent to the original ones, constitutes a complete telephone transmission system. Good transmission systems permit the users to talk to each other easily and naturally, free from the disturbance of extraneous noises and safe from electrical hazards, at costs which are in balance with the expected revenues. Poor systems fail to meet one or more of these conditions. Providing good transmission systems requires the establishment of basic transmission objectives, the design of individual components, assembly of these components into systems which will meet the established objectives, and the proper operation and maintenance of these systems.

The Telephone Company is a service organization. In the final analysis, what is the service we sell? Isn't it the ability for one person to talk with another who is some distance away? In other words, the only real product the company has to offer is transmission. How is this service provided? Stated simply, it consists of the furnishing of transmission systems upon demand between two points. The problem has three elements:

a. Switching Systems - finding the distant end promptly and accurately.

b. Transmission - assuring a satisfactory talk over the interconnected systems.

c. Cost - providing the service at a reasonable cost.

Because the company is a private enterprise, it must make a profit from its operations to stay solvent and continue its existence. This fact must be recognized in everything that we do. It is essential that all of us keep clearly in mind the objectives of the telephone business. We must know where we are now and where we are going, remembering that the only product the Telephone Company has to offer is transmission.

The telephone business consists of the leasing of transmission systems to customers, practically upon demand, to carry a signal or intelligence from one place to another. These signals are of several types:

Speech	- telephone service
Telegraph	- leased lines, TWX
Music	- program lines
Light	- TV networks
Data	- SAGE, telemetering circuits

The essential thing which the various types of signals have in common is that some element of variation is present in their origin or source, for without variation no intelligence can be transmitted. So long as there is some element of variation which can be converted to a varying electrical current, there is a potential service.

Most of the transmission work is handled by specialists. However, in a broad sense, practically all of the functional groups of a telephone organization contribute to the overall transmission performance of the System. Commercial representatives must sell the correct service for the customer's needs. Traffic people must establish operating methods and traffic routings in accordance with the limitations of the plant available. In the design, construction and maintenance of outside plant and central office equipment there are many points at which transmission performance may be vitally affected. It is highly desirable, therefore, that all groups in the Telephone Company have an appreciation of the nature of transmission engineering work and some acquaintance with the fundamental principles employed in it.

This booklet has been prepared as an aid in disseminating such an appreciation. In it an attempt has been made to present some of the underlying principles of transmission engineering in a simple and non-technical way. An acquaintance with the fundamentals of electricity and magnetism has been assumed, but only elementary mathematics have been used in the discussions. No pretext of originality is intended. Material has been drawn from the practices, articles of Bell System authors, and training literature of other Associated Companies.

CHAPTER 1

SOUND, SPEECH, AND HEARING

The primary source of the electrical signals to be transmitted over a telephone system is a speech sound wave, and the end product of the transmission system is a reproduction of the original sound wave. Some knowledge of speech and hearing characteristics is therefore a prerequisite to the study of telephone transmission problems.

Nature of Speech Sounds

The majority of the speech sounds are produced by the vocal chords, a pair of muscularly controlled strips on both sides of the larynx, which form a straight slit through which the breath passes. The expulsion of air from the lungs sets these cords into vibration, producing a complex buzzer-like tone, rich in harmonics. Selective reinforcement of particular frequencies in this complex tone by a combination of fixed and variable resonating cavities within the nose and throat produces the distinctive sounds of the vowels, diphthongs and transitionals. Some consonants, such as p and f, are unvoiced, the sound being produced by the action of the lips, teeth and tongue on the air stream without use of the vocal cords, and other sounds (the voiced consonants, such as v, b, z, or d) are formed by a combination of the two processes. The resultant sound pressure wave is highly complex, containing frequencies ranging from about 100 cycles per second to 10,000 cycles per second, although not all of the range is used for each individual sound.

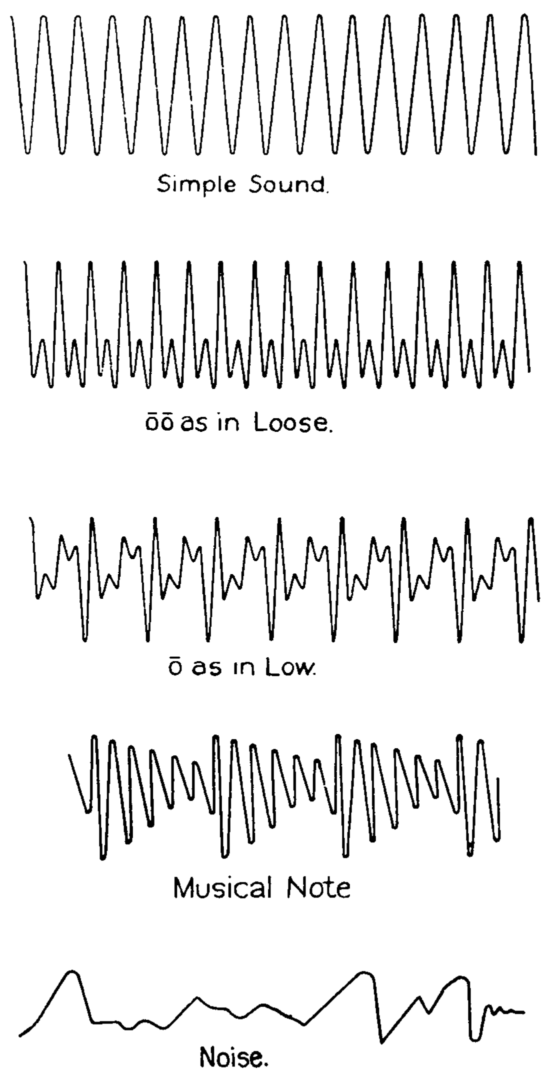

Figure 1-1. Wave Forms

Figure 1-1 illustrates wave forms for different kinds of sound and shows the predominating wave shapes of certain spoken vowels. While these are shown for convenience as transverse waves, in which case the displacements are at right angles to the direction of propagation, it should be remembered that the actual sound waves are longitudinal, consisting of alternate compressions and rarefactions of the air.

The power of the speech waves is extremely small, the average power for average talkers being about 10 microwatts (i.e., ten millionths of a watt). In other terms, five million people talking at once produce about the amount of power required to operate a small radio receiver or light a 50 watt lamp. The instantaneous power, however, frequently reaches peaks of the order of 2000 microwatts. For very loud talking the average power is about 1000 microwatts and, for a soft whisper, about 0.001 microwatt.

A detailed analysis of speech sounds indicates that most of the power is to be found in the vowels, which are ordinarily in the lower frequency range. The consonants, on the other hand, while carrying less energy, are very important to articulation (the correctness with which speech sounds are perceived over a transmission system).

Music differs mainly from other sounds by being sustained at definite pitches for a comparatively long period and by having the changes in pitch take place in definite steps known as the musical interval. For two reasons the transmission of music demands a much wider band of frequencies than does the voice. In the first place music covers a much wider band, and secondly, naturalness is of great importance; in the transmission of speech, naturalness is secondary and intelligibility is the prime consideration. This requires an upper limit of about 10,000 cycles for the best transmission of music.

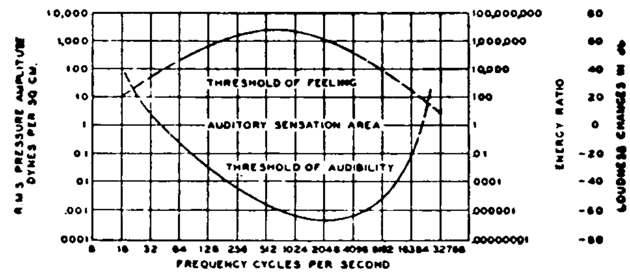

Figure 1-2. Auditory Sensation Area

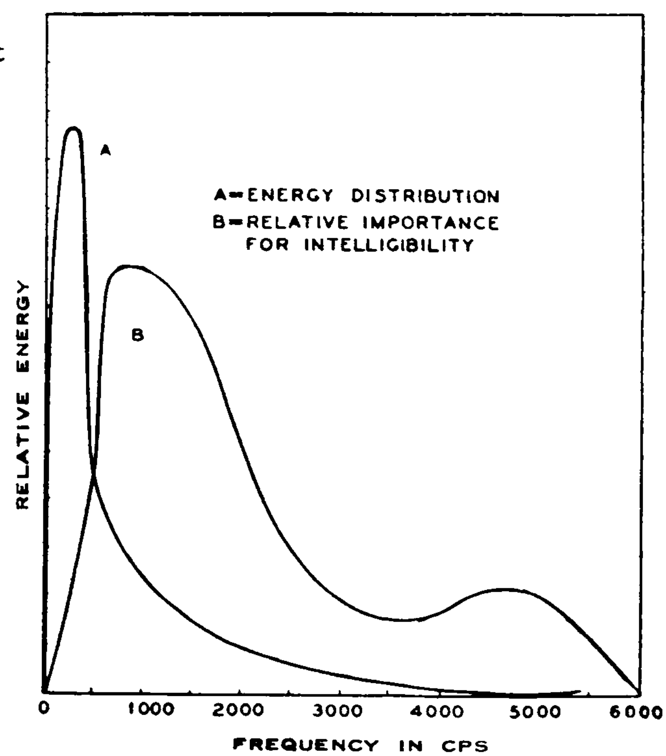

Figure 1-3. Frequency Characteristics of Speech

Hearing

In order to study the hearing process, it is convenient to investigate the response of the ear to pure, single tones of varying amplitude. The response characteristic of the average human ear for such tones is shown in Figure 1-2. The lower curve represents the minimum R.M.S. (root mean square) pressure which is audible and the upper curve shows the limit at which increasing pressure results in a sensation of feeling and where a slight further increase would cause pain. The area enclosed by these two curves, the auditory sensation area, covers the entire useful hearing range. It can be seen that the frequency range of the ear is from about 30 to 20,000 cycles per second and that it responds to sound pressures from below 0.001 dyne per square centimeter to over 1000 dynes per square centimeter. In more familiar units, this corresponds to a range from 1.45×10^{-8} pounds per square inch to 0.0145 pounds per square inch. The extreme sensitivity of the ear is indicated by the fact that, since the normal atmospheric pressure is about 14.7 pounds per square inch, pressure changes of as little as one-billionth of this can be perceived as sound. Some 300,000 separate pure tones differing in pitch and loudness are contained in the auditory sensation area, and probably a much greater number of complex tones can be distinguished. Relative energy levels for intelligible speech are shown in Figure 1-3.

Frequency Band Requirements for Speech Transmission

The relative importance of the various frequency regions of speech is of interest to transmission engineers in determining the response characteristic of the plant to be used. This effect has been studied by setting up high quality electrical systems for the transmission of speech and then inserting either high-pass or low-pass filters to remove certain portions of the speech band. (The high-pass filter passes all frequencies above a certain value and eliminates those below this value; the low-pass filter passes all frequencies below a particular value and eliminates those above this value.) The results of one series of tests are shown in Figures 1-4 and 1-5. It will be noted that, if all frequencies below 1000 cycles per second are eliminated, the energy is reduced to about 17 percent of that carried by the entire band of frequencies; the articulation,* however, is about 85 percent of that given by a circuit passing all frequencies equally well. On the other hand, if all frequencies above 1000 cycles per second

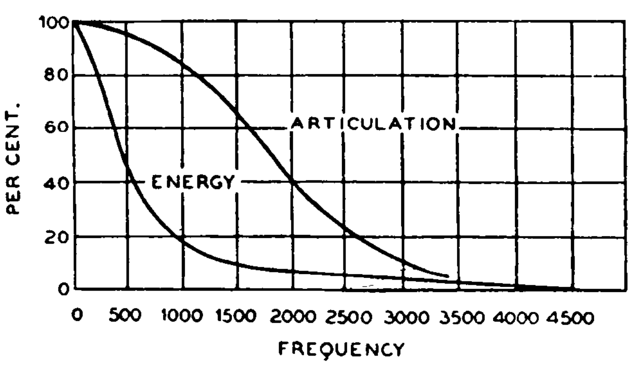

Figure 1-4. Effect on the Articulation and Energy of Speech Due to Elimination of Frequencies by High Pass Filters.

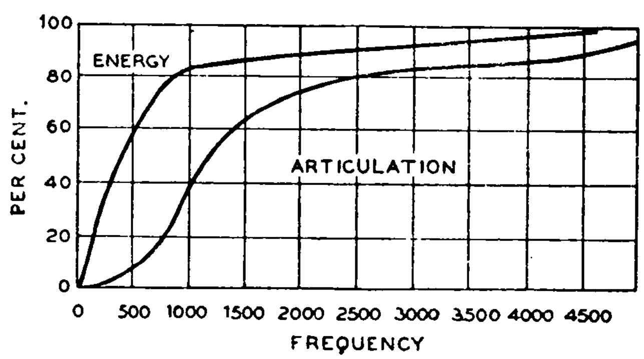

Figure 1-5. Effect on the Articulation and Energy of Speech Due to Elimination of Frequencies by Low Pass Filters.

* A number of meaningless speech syllables (such as: jod, sim, ha) were transmitted through the system. The percentage of these syllables correctly understood is plotted as "Percent Articulation" in Figures 1-4 and 1-5.

are eliminated, the articulation is only 40 percent, although about 83 percent of the total speech energy is being transmitted.

Clearly the high frequency components play a very important part in contributing to the intelligibility of speech, even though their energy content is relatively small, and this must be recorgnized in design work. At the present time, transmission of the band from about 250 to 3500 cycles per second is considered to be of satisfactory quality for speech. Where a band width of less than this is used, allowance is made for the additional distortion.

Effect of Noise on Speech Transmission

When speech is transmitted either directly or over an electrical system there is always an interference to the proper reception of such speech because of the presence of other sounds. These extraneous sounds, which serve only to interfere with reception of the desired signal, may be broadly classed as "noise", even though in themselves they may be pleasing. In other words, noise to the transmission engineer is any sound in the wrong place. It may arise from inductive effects between telephone lines and power lines, from disturbances originating within the telephone plant such as key clicks or cross-talk between adjacent circuits, or as ambient noise at the transmitting or receiving location. In any case, the presence of noise tends to mask the desired signal by reducing the ability of the ear to detect its presence. In effect, the threshold of hearing is raised by an amount which depends on both the volume and the frequency components of the interference. Some idea of the magnitude of this effect may be gained from the following table:

Typical Place	Maximum Hearing Distance for Average Speech
Soundproof Room	250 feet
Average Office	40 feet
Noisy Office	12 feet
Subway Train	15 inches
Boiler Factory	1.5 inches

In telephone practice the noise interference problem may be attacked in two ways. Either the volume of the signals must be raised to compensate for the shift in the hearing threshold, or attention must be directed toward eliminating the noise at its source or suppressing it at the point where it enters the telephone plant. The solution is often an economic compromise between the two methods.

Frequency Band for Other Services

The preceding discussion has been directed principally toward establishing the wire transmission requirements for normal telephone service. In addition, the wire facilities may be used for the transmission of ringing, signaling and telegraph impulses below 250 cycles per second; special services such as radio program circuits may require the extension of the upper frequency limit to 10,000 or 15,000 cycles per second, and with sufficient amplification the same facilities may be used for carrier circuits requiring an upper frequency of around 260 kilocycles per second. In addition to the extension of the frequency ranges required for such services, it is frequently necessary to handle greater volume ranges than those encountered in normal speech, and a corresponding improvement in noise conditions is often required.

CHAPTER 2

NETWORKS

The transmission of any intelligence to a remote point by electrical means involves three essential processes:

a. Converting the original signal to an electrical impulse which varies in a manner similar to the signal.

b. Passing this impulse through a series of connected electrical networks until the receiving point is reached.

c. Reconverting the electrical impulse to a signal of appropriate form.

The original signal may have many forms, the common characteristic being that some varying element is present. Thus, for sounds, variations in air pressure are involved; for pictures, variations in light intensity; for remote gauging, mechanical variations such as the height of a float. These variations in the original signals, when translated into electrical impulses, may have a wave form ranging from the simple (e.g., a rectangular pulse of direct current) to the highly complex. Speech and the resultant electrical waves consist of a series of transients* and, if it were not for that one fact, the mathematical analysis of the electrical portion of the transmission process would be a hopeless task.

Fortunately, it can be shown that any recurrent electrical wave may be resolved into a series of single frequency waves of the form of a sine wave. Similarly, any transient voltage may be expressed as a continuous band of frequencies and the response of the electrical network to this impressed voltage is a current which can also be expressed as a continuous band of frequencies. Furthermore, the ratio of the voltage to the current for any particular frequency component is given by the steady-state impedance of the network at that frequency. While the actual analysis is only rarely attempted, the knowledge that it is theoretically possible governs the whole philosophy of transmission analysis and leads to the classical method of attacking the problem by means of single frequency sine wave computations.

Obviously no single frequency is completely representative of a complex electrical wave. However, for many purposes in telephone transmission analysis, the performance of a circuit or piece of equipment over the voice

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* The currents in an electrical circuit are said to be in a transient state in the interval of time between a change in an e.m.f. or impedance in the circuit and the establishment of a steady state. During this interval currents flow which usually increase or decrease rapidly with time.

range of frequencies may be roughly judged from a knowledge of its performance at a frequency of around 1000 cycles per second. This procedure has the merit of simplicity, with the accompanying defect that it ignores the noise and quality elements of the transmission process. Where comparisons are made between circuits and equipment having essentially the same frequency response and noise characteristics, then the differences in volume at 1000 cycles per second are indicative of the relative merits of the various arrangements. The results of computations at this frequency are designated as "volume" losses or gains to distinguish them from ratings including the effects of noise and distortion which are called "effective" or "subjective" losses. This chapter is largely devoted to volume considerations. Transmission rating systems are discussed in a later chapter.

The actual transmission of the electrical wave from transmitter to receiver is accomplished by transferring energy from one electrical network to the next, until the circuit terminal is reached. Before any quantitative analysis of the telephone transmission process can be attempted, therefore, it is necessary to review some general principles of alternating current networks.

An electrical network is an assembly of resistors, inductors and capacitors and, in certain cases, control devices such as electron tubes. The usual resistors and capacitors are linear (i.e., the current is directly proportional to the voltage) and bilateral (i.e., they are capable of transferring energy equally well in either direction). This is also true of air-core inductors. Iron-core inductors, while bilateral, are not usually linear but may frequently be considered so over the limited ranges of current used in telephony. Control devices are generally unilateral and involve a local source of power which is controlled by the input signal.

In the analysis of the usual electrical networks making up communication circuits, Ohm's and Kirchoff's laws are the primary tools. By the aid of these, certain other principles have been derived which are of considerable assistance in minimizing the effort required for network analysis.

Ohm's Law

The current I which will flow through an impedance Z is equal to the voltage divided by the impedance, or $I = \frac{E}{Z}$.

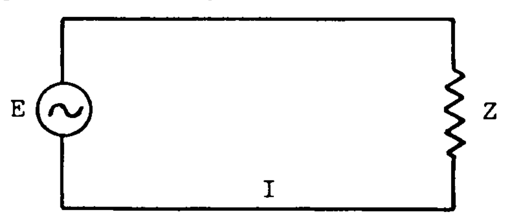


Figure 2-1. Simple Series Circuit Containing an Impedance Z.

$$I = \frac{E}{Z}$$

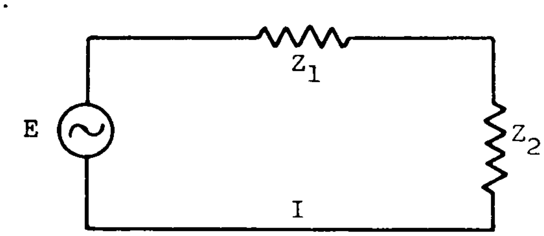


Figure 2-2. Simple Series Circuit Containing Two Impendances Z_1 and Z_2.

$$I = \frac{E}{Z_1 + Z_2}$$

Kirchoff's Laws

Law I: At any point in a circuit, there is as much current flowing to the point as there is flowing away from it. At point a in Figure 2-3,

$$I_1 = I_2 + I_3$$

Law II: In any closed electrical circuit, the algebraic (or vector) sum of the electromotive forces (emf's) and the potential drops is equal to zero. In Figure 2-3,

$$E = I_1 Z_1 + I_3 Z_3$$
$$E = I_1 Z_1 + I_2 Z_2$$
$$I_2 Z_2 - I_3 Z_3 = O$$

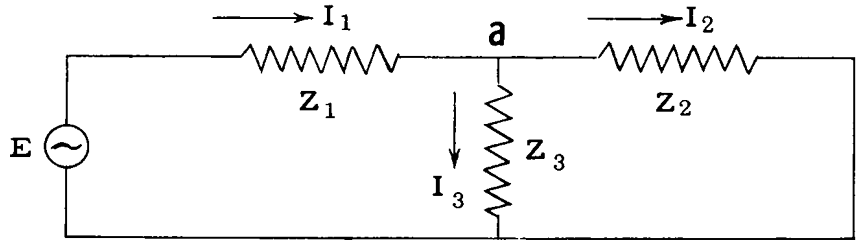
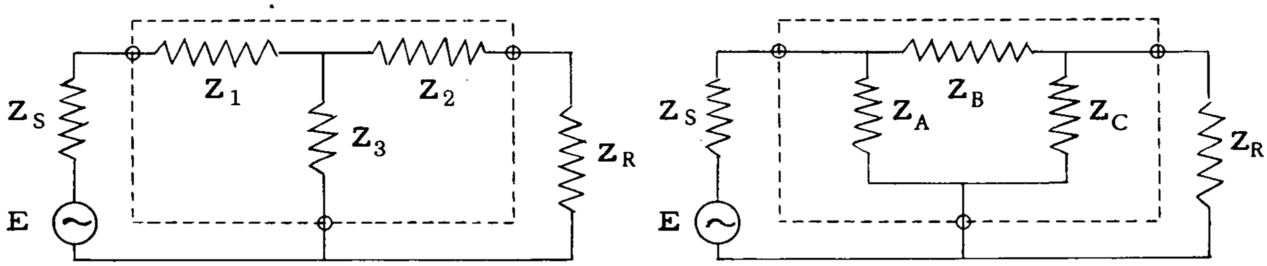


Figure 2-3. Simple Series-parallel Circuit.

The application of these laws to more complicated circuits involves setting up simultaneous linear equations for solution. This can be very laborious in the practical case, and several theorems, known as network theorems, have been developed to expedite this process. Two important types of networks are called, from their configurations, the T and π network. (π is the sixteenth letter in the Greek alphabet; it is pronounced in the same way as the English word "pie".)

Equivalent Networks

In any network at a single frequency, a 3-element T structure can be interchanged with a 3-element π structure, provided certain relations exist between the elements of these two structures.



(A) T - Network (B) π - Network

Figure 2-4. Equivalent Networks.

Figure 2-4 represents a connecting circuit between a generator of emf E, with impedance Z_S, and a receiver of impedance Z_R. If the impedances enclosed in the boxes are related by the relationships shown below, one box may be substituted for the other without affecting the voltages or currents in the circuit outside the boxes.

π to T	T to π
$Z_1 = \dfrac{Z_A Z_B}{Z_A + Z_B + Z_C}$	$Z_A = \dfrac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_2}$
$Z_2 = \dfrac{Z_B Z_C}{Z_A + Z_B + Z_C}$	$Z_B = \dfrac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_3}$
$Z_3 = \dfrac{Z_C Z_A}{Z_A + Z_B + Z_C}$	$Z_C = \dfrac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_1}$

This property of networks permits any 3-terminal structure, no matter how complex, to be reduced to a simple T. For example, a π to T transformation permits converting the circuit in Figure 2-5 to that shown in Figure 2-6. By combining Z_3 with Z' and making a second π to T transformation, Figure 2-6 can be reduced to a simple T.

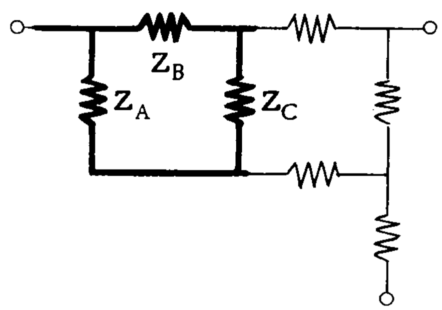


Figure 2-5.

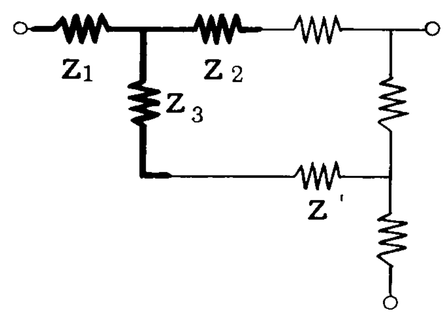


Figure 2-6.

These relationships apply only to networks having three terminals. Similar relations can be developed for 4-terminal networks (frequently called four-poles). Figure 2-7 (A) is a typical four-pole. If only voltages measured between terminals a and b and between terminals c and d are significant, the five impedances (A) can be replaced with the T structure (B).

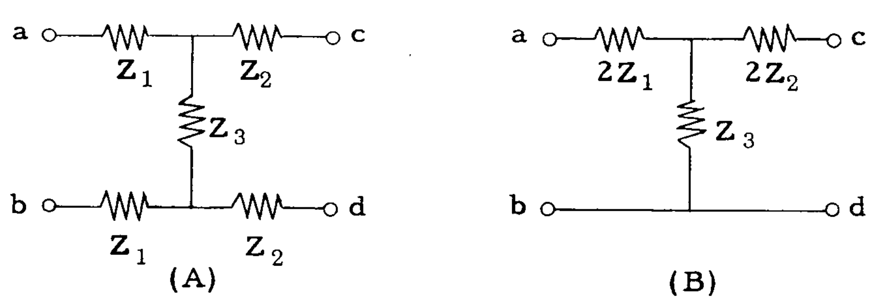


Figure 2-7. Equivalent Four-poles.

Superposition Theorem

If a network has two or more generators, the current through any component impedance is the sum of the currents obtained by considering the generators one at a time, each of the generators other than the one under consideration being replaced by its internal impedance.

Multi-generator networks can be solved by Kirchoff's Laws, but their solution by Superposition requires less complicated mathematics. Perhaps of even greater importance is the fact that this Theorem is a useful tool for visualizing the currents in a circuit.

Before we consider what the statement of the Superposition Theorem means with an example, it may be well to review the concept of "the internal impedance of a generator". We know that the open-circuit voltage of a battery will be greater than the voltage across the terminals of the same battery when supplying current to a load. The emf of the battery is a fixed value. It is determined by the electrochemical properties of the materials from which the battery is made. The voltage we measure in the open circuit condition is this emf. Under load, the decrease in terminal voltage will be the IR drop across the internal resistance of the battery. If it were possible to construct a battery from materials that had no resistance (and polarization could be eliminated), the battery would have no internal resistance and no internal voltage drop. Lacking materials with infinite conductivity, every practical voltage source can be resolved into a pure potential (emf) in series with an internal resistance or impedance.

Getting back to Superposition, perhaps the Theorem can be most easily explained by working out a simple problem. In Figure 2-8, which way does the current flow in the 10-ohm resistor?

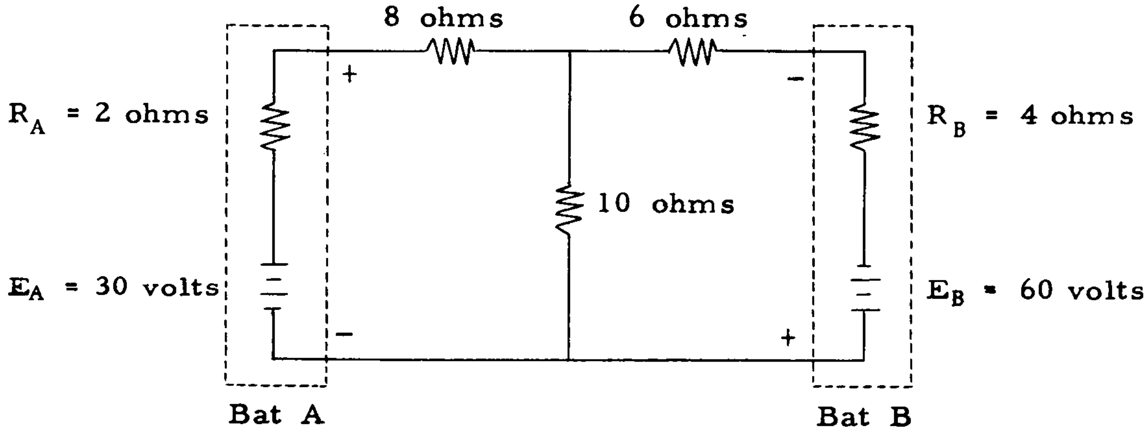
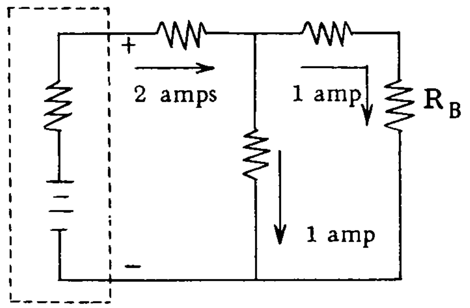


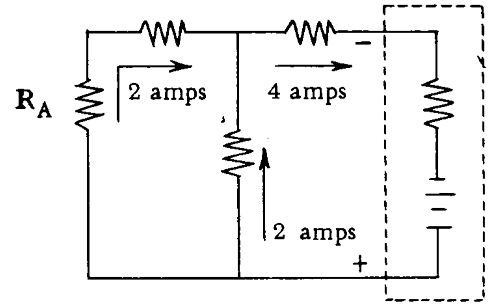
Figure 2-8.

Our Theorem says to determine the currents caused by each battery in turn, with all other batteries replaced by their internal resistances. Ohm's law gives us the currents indicated in Figures 2-9 and 2-10.



Bat A

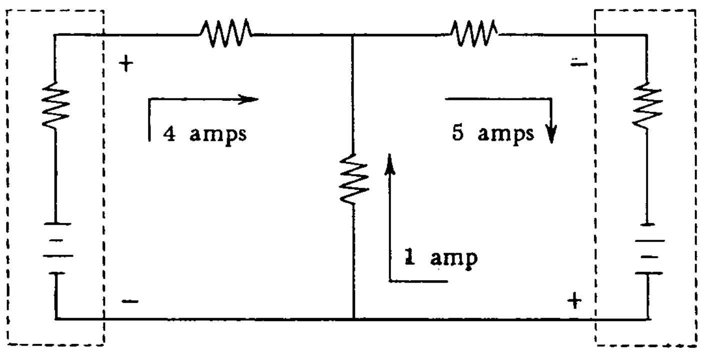
Figure 2-9.



Bat B

Figure 2-10.

The currents flowing in the circuit with two batteries will be the sum of these component currents. Of course, sum means algebraic sum (or vector sum if the problem is ac) and currents flowing in opposite directions subtract.



Bat A Bat B

Figure 2-11.

The resultant currents are shown in Figure 2-11, and we see that the 10-ohm resistor carries one ampere upward. We could have estimated the direction of the current in the 10-ohm resistor by inspection, since the resistances are symmetrical and the 60-volt battery will produce the larger component of current. But going through the arithmetic illustrates the application of the Theorem.

Thevenin's or Pollard's Theorem

For the purpose of simplifying electrical calculations, we can consider any electric system, such as shown in Figure 2-12, as one network supplying energy to another. The first of these networks may then be replaced by an equivalent simplified circuit, which consists of an emf and an impedance in series, as shown in Figure 2-13.

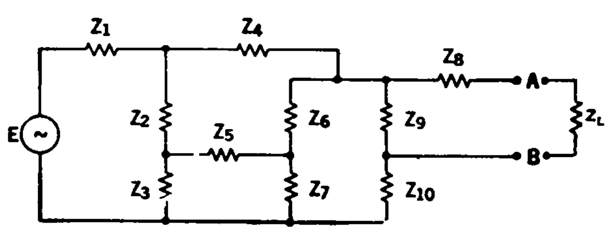


Figure 2-12. Network System.

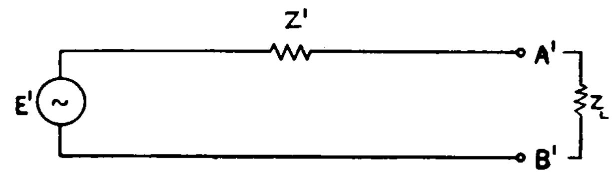


Figure 2-13. Application of Thevenin's Theory to the Network of Figure 2-12.

The equivalent emf, E' in Figure 2-13 will be the open-circuit voltage at terminals AB of Figure 2-12. And the equivalent impedance Z' will be the impedance presented at terminals AB when E is made zero. Another way of defining Z' is to say that it is the open-circuit voltage at AB divided by the short-circuit current at AB. Under these conditions, a load connected to A'B' will draw the same current as when connected to AB.

Maximum Power Transfer

In Figure 2-14, E and Z_1 represent a source of power. This source may be a telephone instrument, a repeater amplifier, or the sending side of any point in a telephone connection. Z_2 is the load which receives the power transmitted. It may be another telephone instrument or a radio antenna — the receiving side of any point in a connection. The amount of power transferred from the source to the load will be determined by the relative values of Z_1 and Z_2.

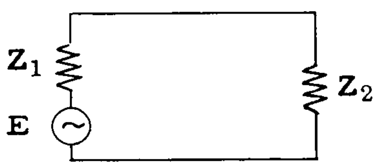


Figure 2-14.

a. If Z_1 is an impedance and there is no restriction on the selection of Z_2, the power transferred will be a maximum when Z_2 is the conjugate of Z_1. That is, when both Z_2 and Z_1 have equal components of resistance, but the reactive components are equal and opposite — one inductive, the other capacitive ($R_2 = R_1$ and $X_2 = -X_1$).

b. If Z_1 is an impedance and the magnitude of Z_2 can be selected, but not its angle, the power transferred will be a maximum when the absolute values of Z_2 and Z_1 are equal ($|Z_2| = |Z_1|$). That is, the impendances are equal disregarding phase.

c. If both Z_1 and Z_2 are pure resistances, the power transferred will be a maximum when the source and load resistances are equal ($R_2 = R_1$).

The pure resistance case ("c" above) has been plotted in Figure 2-15 to illustrate the principle. Curves of power and efficiency are drawn over the range R_2 equals zero to R_2 equals twice R_1. When R_2 is zero (a short-circuit), the current is at its maximum possible value. The power (I^2R_1) is also at the highest possible value, but it is all dissipated in the source resistance R_1. As R_2 is increased, the current and total power ($I^2R_1 + I^2R_2$) decreases; however, a portion of the power will be dissipated in the load R_2. Curve A shows that the power dissipated in the external circuit (or load) is a maximum when $R_2/R_1 = 1.0$ or $R_2 = R_1$.

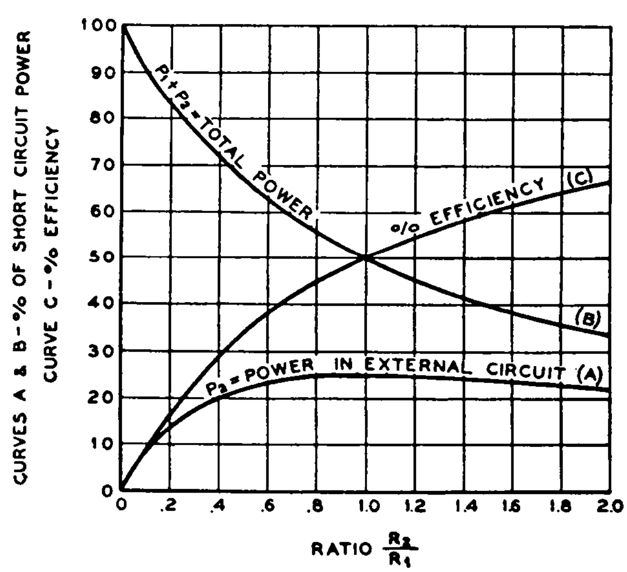


Figure 2-15. Maximum Power Transfer.

Under this condition, the efficiency is only 50 percent. Half of the total power is dissipated in the source and half in the load. This approximates the desirable condition in telephony, since in most telephone application we are interested in receiving all the power possible regardless of the efficiency.

Actually, most telephone circuits contain some reactance so that condition "a" above (where the load impedance is the conjugate of the source impedance) would appear optimum. However, we shall see in the discussion of transmission lines that conjugate termination will cause reflections or echo. Therefore, we usually compromise on condition "b" above and choose a load impedance of the same absolute magnitude as that of the source.

Transformers

Repeating Coils - The applications of transformers to telephone circuits are numerous and varied. Inequality transformers, or repeating coils, are used in most cases primarily to match unequal impedances to permit maximum energy transfer. One very general use is to transfer, with very little loss, electrical energy from one circuit, such as a common battery cord circuit, to another without any metallic connection being made between the two circuits; from a direct current aspect the circuits are separate units. In power work the principal use of a transformer is to step-up or step-down voltages.

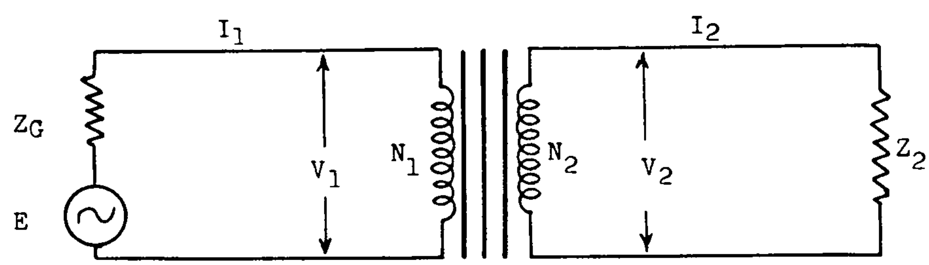


Figure 2-16. Transformer Circuit.

The currents through the two windings of a transformer are inversely proportional to the number of turns in the two windings. The voltages across the two windings are directly proportional to the number of turns in the two windings.

Since no power is lost in the ideal transformer and the phase relation between the voltage and current on the two sides of the transformer is exactly the same, the product of the voltage V_1 across the primary and the current I_1 through the primary winding is equal to the corresponding product for the secondary winding. That is

$$V_1 I_1 = V_2 I_2 \text{ or } \frac{V_1}{V_2} = \frac{N_1}{N_2} \text{ and } V_1 N_2 = V_2 N_1$$

Substituting the value of $\frac{V_1}{V_2}$,

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

Now $V_2 = I_2 Z_2$

Substituting the values of $V_2 = \frac{V_1 N_2}{N_1}$ and $I_2 = \frac{I_1 N_1}{N_2}$ as determined from above,

$$V_1 \left(\frac{N_2}{N_1}\right) = \left(\frac{I_1 N_1}{N_2}\right) Z_2$$

Then

$$\frac{V_1}{I_1} = Z_1 = \left(\frac{N_1}{N_2}\right)^2 Z_2$$

The impedance Z_1 across the terminals of the primary winding of a transformer when the secondary winding is closed through an impedance Z_2 is equal to the square of the ratio of the number of turns in the two winding times Z_2.

In an ideal transformer no power is lost. Commercial transformers approach this efficiency very closely. A small amount of loss is occasioned by currents induced in the core itself (eddy current losses) and in the setting up of the necessary flux in the core (hysteresis losses).

Phantom Circuit Theory - Another very general use of repeating coils in the telephone plant is for deriving "phantom" circuits. Here the coils serve a unique purpose which has no counterpart in electric power work.

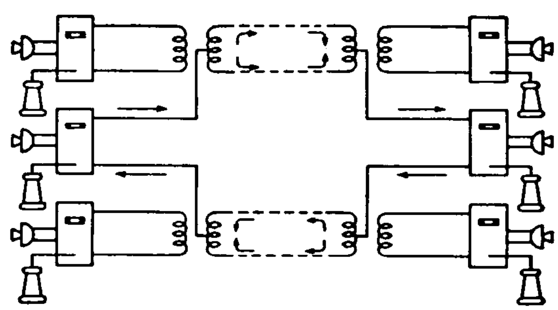


Figure 2-17. Principle of the Phantom Circuit.

Figure 2-17 is a simplified diagram of two adjacent and similar telephone circuits arranged for phantom operation. By means of repeating coils installed at the terminals of the wire circuits, a third telephone circuit is obtained. This third circuit is known as the phantom and utilizes the two conductors of each of the two principal, or "side", circuits as one conductor of the third circuit. The two side circuits and the phantom circuit are together known as a phantom group. These three circuits, employing only four line conductors, can be used simultaneously without interference with each other, or without crosstalk between any combination, provided the four wires have identical electrical characteristics and are properly "transposed" to prevent crosstalk.

The repeating coils employed at the terminals are designed for voice current and ringing current frequencies, and do not appreciably impair transmission over the side circuits. The third or phantom circuit is formed by connecting to the mid-points of the line sides of the repeating coil windings, as shown in Figure 2-17. Since the two wires of each side circuit are identical, any current set up in the phantom circuit will divide equally at the mid-point of the repeating coil line windings. One part of the current will flow through one-half of the line winding, and the other part of the current will flow in the opposite direction through the other half of the line winding. The inductive effects will be neutralized, and there will be no resultant current set up in the drop or switchboard side of the repeating coil. Since the phantom current divides into two equal parts, the halves will flow in the same direction through the respective conductors of one side circuit, and likewise return in the other side circuit. At any one point along a side circuit there will be no difference of potential between the two wires due to current in the phantom circuit, and a telephone receiver bridged across them will not respond to the phantom conversation.

Since there is no connection, inductive or otherwise, between the two circuits at the terminals, it is equally true that a conversation over a side circuit cannot be heard in the phantom.

In the theory of the phantom it should be remembered that the conductors are assumed to be electrically identical, or in other words, the conductors are perfectly "balanced". The phantom is very sensitive to the slightest upset of this balance, and circuits that are sufficiently balanced to prevent objectionable crosstalk or noise in physical circuit operation, may not be sufficiently balanced for successful phantom operation.

<u>Hybrid Coils</u> - In telephone repeater operation we must receive incoming energy and direct it into a receiving circuit (input) which is separate and distinct from the sending (output) circuit. This is necessary because the device used for amplifying voice frequency currents operates in one direction only. The use of such one-way amplifiers, without some device for securing transmission in both directions would require not only twice the circuit facilities for each long distance connection, but also special telephones at each terminal. It would not be possible for two such amplifiers to be connected at the same point in a telephone circuit, because any energy amplified in one circuit would be delivered to the input of the other to be amplified again and returned to the first. This returning energy would again reach the input of the first amplifier and the cycle would be repeated. Energy circulating through the two amplifiers would increase in value until a condition of saturation was reached. The repeater would then continue to oscillate or "sing" indefinitely, rendering the telephone circuit inoperative.

Although a simple inequality ratio repeating coil must provide for connecting together two unequal impedances, the hybrid coil must provide for matching four impedances. This is illustrated in Figure 2-18. If Z_1 is the impedance of the telephone line and Z_2 the impedance of the balancing network, Z_1 should be equal to Z_2. In order to determine the relationships between Z_3 and Z_4, which represent the impedance of one amplifier input and the impedance of the other amplifier output, respectively, we must analyze the electrical conditions.

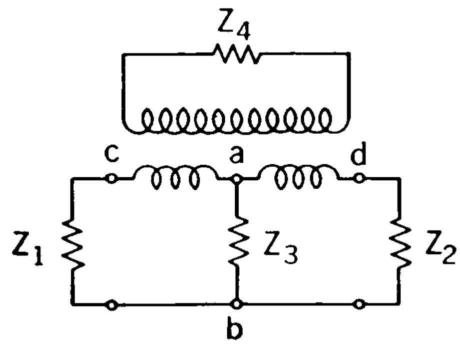


Figure 2-18. Hybrid Coil for Matching Four Impedances.

If we represent the source of voltage in the output circuit by a generator connected in series with Z_4, the energy supplied to the coil will obviously divide equally at the bridge, one-half going to each of the two equal impedances, Z_1 and Z_2. None will get to Z_3. The part going to Z_2, which represents the impedance of the network circuit, accomplishes no useful purpose and is lost. For this reason alone, the amplifier must be adjusted to supply twice the energy that is required for actual transmission. If, now, we simulate the conditions for inward transmission, connecting the generator in series with Z_1, the coil relations are such that half the energy goes to Z_3 and half is dissipated in Z_4, but none reaches Z_2. The voltage induced between c and a is equal to the voltage induced between a and d because the windings have the same number of turns and are on the same magnetic core. The turn ratio of the coil is fixed at such a value that the voltage induced in the latter winding is just equal to the voltage drop across Z_3. Consequently, points b and d are at the same potential. There is, therefore, no current flow between these points, and Z_2 consumes no energy. As before, however, half the incoming energy is lost in the impedance Z_4, so the amplifier must be further adjusted to compensate for this additional loss.

Hybrid coils are used in connection with 2-wire telephone repeaters to accomplish the "double-tracking" purpose that we have been considering. The same three-winding coil can be used at the terminals of 4-wire circuits to convert the 4-wire line into a 2-wire line, where it behaves in exactly the same way as in the 2-wire repeater circuit. More commonly, however, a slightly different transformer arrangement is used for this purpose. This consists of two ordinary repeating coils connected with one winding reversed.

Where repeating coils having six windings are used in a hybrid arrangement, the connections are naturally somewhat different, but the general theory is the same.

Series Resonance - All electrical circuits, no matter how simple, contain resistance, inductance, and capacitance. For given values of inductance and capacitance, a circuit will react differently to a "critical frequency", as contrasted to all other frequencies.

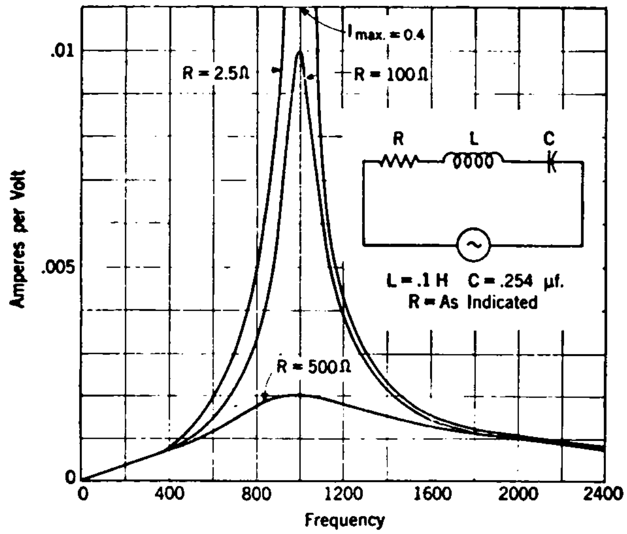


Figure 2-19. Curves of Current Values in Series Resonant Circuit.

In a resonant circuit, or one having the inductance and capacitance in series, the reactance is zero whenever the inductive and capacitive reactances are equal in magnitude, or when $X_L = X_C$. The frequency at which this occurs is called the "resonant" or "critical" frequency. At resonance, the impedance has a minimum value and is equal to the resistance of the circuit. If this resistance is small a large current will flow as compared to the current flowing at other frequencies, as shown in Figure 2-19.

Parallel or Anti-Resonance - In an anti-resonant circuit, or one having the inductance and capacitance in parallel, the impedance of the combination is a maximum when the inductive and capacative reactances are equal in magnitude, or when $X_L = X_c$. The frequency at which this occurs is called the "anti-resonant" frequency of the circuit. For anti-resonant circuits at resonant frequency the impedance is a maximum and the current, therefore, a minimum. The selectivity of the circuit is decreased as the resistance is increased, reaching a point where the circuit loses its resonant characteristics altogether.

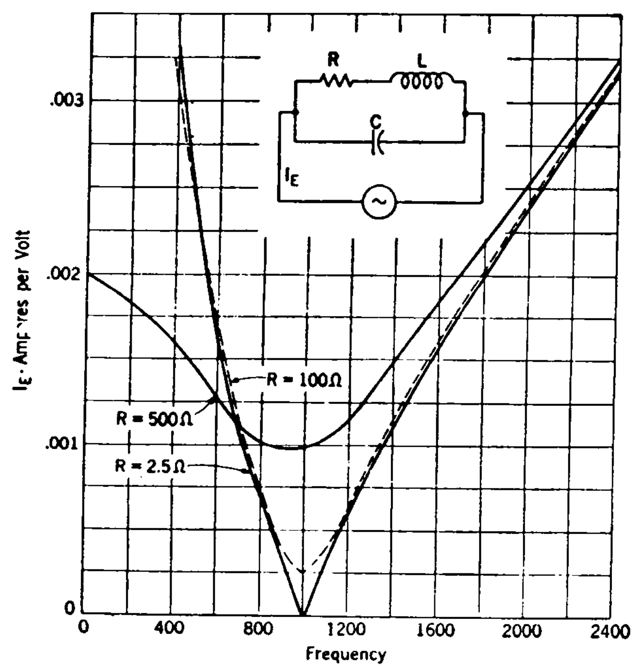


Figure 2-20. Curves of Current Values in Parallel Resonant Circuit.

In both the series and parallel circuit, resonance occurs when the inductive and capacitive components of reactance are equal. That is, when

$$X_L = X_c = 2\pi f L = \frac{1}{2\pi f C}.$$

Therefore, the resonant frequency

$$f_r = \frac{1}{2\pi\sqrt{LC}}.$$

We have seen that the sensitivity at resonance is determined by the amount of resistance in the circuit. Since the resistance is usually concentrated in the inductor, the objective is to have the ratio of the reactance of the inductor to its resistance as high as possible. This ratio is known as quality, or Q, of the inductor and is expressed by

$$Q = \frac{X_L}{R} = \frac{2\pi f L}{R}$$

The resonance principle has numerous and interesting uses in connection with communication circuits. One application is the use of a capacitor of proper value in series with a telephone receiver winding, repeating coil winding, or other winding having inductance, where it is desired to increase the current.

A much more common use of the resonance principle is the so-called "tuned" circuit which is so extensively employed in radio and other high frequency applications. It is an arrangement whereby the circuit has a much lower impedance to some particular frequency than to any other frequency, allowing a correspondingly higher current to flow for the particular frequency. In radio and other high frequency work the parallel-resonant circuit is often called a "tank circuit", acting as a storage reservoir for electric energy.

Filters

An electrical network of inductors and capacitors designed to permit the flow of current at certain frequencies with little or no attenuation, and to present high attenuation at other frequencies is called an electric wave filter. The purpose of a filter is to provide a circuit which will readily transmit certain frequencies and suppress all others.

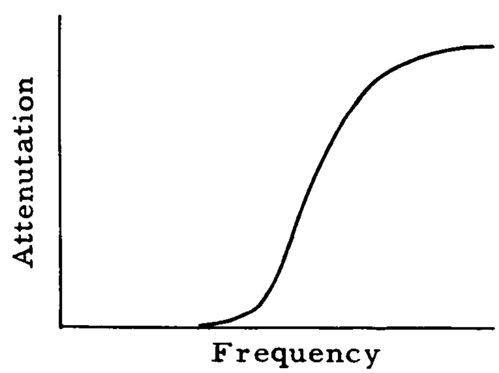


Figure 2-21. Low-pass Filter.

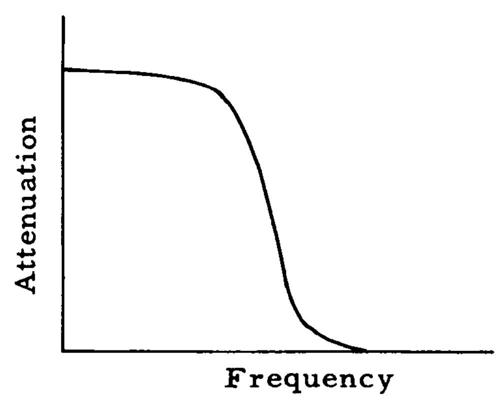


Figure 2-22. High-pass Filter.

Combinations of low-pass and high-pass filters are known as band-pass filters and may be used to stop or to pass an intermediate band of frequencies.

The action of a filter depends upon the simple fact that inductance and capacitance are opposite in their responses to varying frequencies. An inductance passes low frequencies readily and offers an increasing series impedance with increase in frequency, while the reverse is true of capacitance.

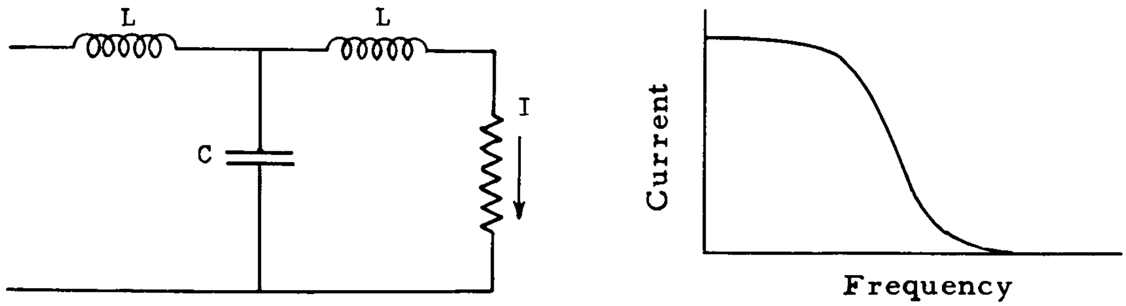


Figure 2-23. Low-pass Filter.

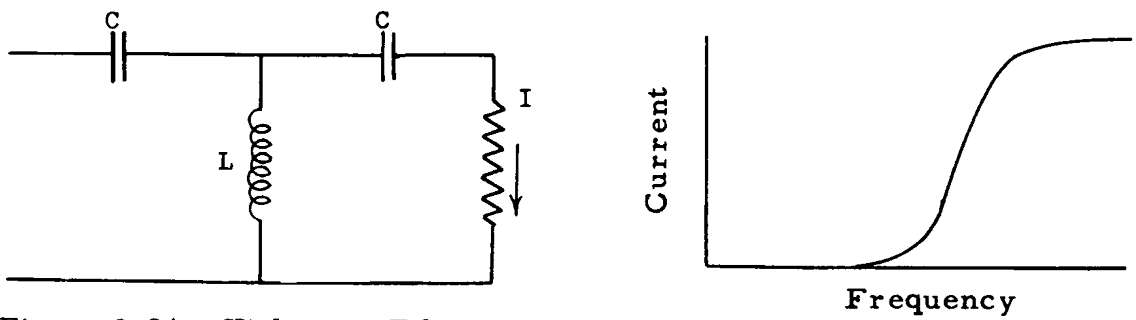


Figure 2-24. High-pass Filter.

Electrical filters have a large number of applications in the telephone art. Carrier systems, composite sets and many central office power plants require their use. In fact, much of the present electronic art has been made possible by their development.

The presence of resistance in the inductors used in filter sections introduces additional losses in the transmitting bands, and reduces the sharpness of cut-off. In telephone and telegraph carrier systems, the number of channels which can be used in a given frequency range depends on the width of the pass band plus the transition bands on each side of it. One of the most practicable ways to obtain a high ratio of reactance to resistance is to use mechanical vibrating systems, such as the piezo-electric crystal. In an electric circuit such as a filter, a crystal acts as an impedance. Crystal filters find wide application in "broad-band" (J, K, and L) carrier systems.

CHAPTER 3

ELECTRONICS

The use of electronic equipment in the communication business is expanding so rapidly that it becomes important for engineers in all branches of the industry to have some knowledge of fundamental electronic theory and of basic electronic components. The use of electronic circuits is no longer confined to radio, television and carrier applications. For example, electronic control circuits now appear in local switching offices. Indeed it appears that all-electronic switching offices will supplant mechanical switching offices in the near future.

Electron Tubes

The electron tube is so named because it utilizes a flow of free electrons in a vacuum or a partial vacuum. Such tubes are used as oscillators, rectifiers, amplifiers, modulators, pulse generators, pulse shapers, etc. They are building blocks which make possible long distance telephony, radio, television and many delicate control systems.

The Electron - The electron is a minute, negatively-charged particle with a mass of 9×10^{-28} *gram. It is the smallest bit of electricity. Lighting an ordinary 60-watt light bulb requires a current of about one-half ampere. In terms of electrons, this means a flow of about 3×10^{18} **electrons per second. For its size, the electron packs a terrific punch, because the charge-to-mass ratio of the electron is enormous. Imagine two spheres composed entirely of electrons, each sphere weighing one gram (1/28 ounce). Because like changes repel, there would be a force tending to push the spheres apart. If the spheres were separated by 100 km (62 miles), the repelling force would still be about three million, million, million tons!

Electrons in Metals - In metallic conductors, some electrons are unbound and free to travel from atom to atom. Such unbound electrons, in the absence of external electric or magnetic forces, assume a chaotic motion. If enough additional energy from an external source is imparted to such unbound electrons, some of them will move toward the surface of the metal with sufficient velocity to break through and become, at least momentarily, free electrons.

Types of Emission - The four principal methods to obtain free electrons from solid metals are:

---

*Or 9 preceded by a decimal point and twenty-seven zeros.
**Or 3 followed by eighteen zeros.

a. Thermal emission, in which the metal is heated to increase the thermal energy of the unbound electrons.

b. Photo-electric emission, in which light energy is transferred to the unbound electrons.

c. Field emission, in which a strong electric field is applied to the surface of the metal.

d. Secondary emission, in which the energy is supplied by electric charges bombarding the surface of the metal.

Flow of Electrons or Current - If free electrons are provided by some method of emission and if a positive collector is nearby, there will be a flow of electrons from the emitter, or cathode, to the collector, or anode. This flow of electrons, or current of electricity, is commonly measured in amperes or milliamperes. (An ampere is one coulomb per second, or 6.24×10^{18} electrons per second.)

The Diode and Its Characteristics - The simplest electronic tube is called a diode because it has only two elements; the cathode and the anode. The cathode is surrounded by the electron-collecting anode, or plate. If the cathode is emitting sufficient electrons and if the diode is connected in series with a suitable battery, with the plate connected to the positive battery terminal, an electron current will flow from the cathode to the plate. No current can flow in the opposite direction. Figure 3-1 illustrates typical diode

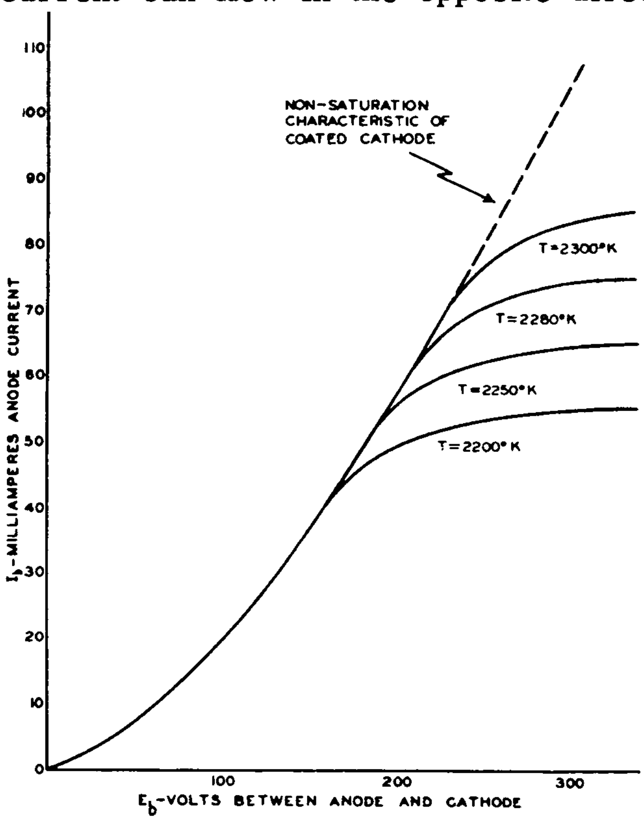


Figure 3-1.

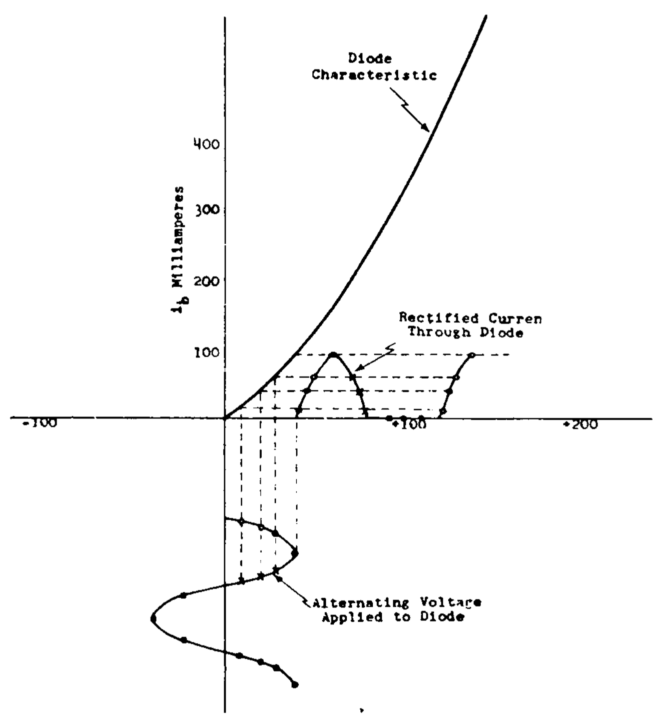


Figure 3-2. Use of Diode Characteristic to Determine Current Flow When Alternating Voltage is Applied.

characteristics. It will be seen that plate current is strongly affected by the plate voltage until the plate voltage is made high enough so that saturation is approached. At the point of saturation all electrons emitted by the cathode are drawn to the plate. Further increase of plate voltage beyond the point of saturation cannot increase the current.

Figure 3-2 shows how a diode characteristic curve can be used to determine the current flow which will result when an alternating voltage is applied to the tube. The use of the diode as a circuit element to provide rectification or detection will be discussed later.

The Triode and its Characteristics - In the triode a third element, called the control grid, is placed between the cathode and the plate. The grid is much closer to the cathode than is the plate; therefore, small changes in grid voltage have relatively great effect on the electron flow (plate current). If the grid is held negative with respect to the cathode, as in the circuit of Figure 3-3, the negative grid voltage will tend to repel the electrons which are emitted by the cathode and will thus reduce the plate current. Indeed, if the grid is sufficiently negative plate current will be cut off entirely. The fact that relatively small variations in grid voltage produce corresponding large variations in plate current permits use of the triode for amplification, oscillation, frequency conversion, modulation, demodulation and other circuit functions.

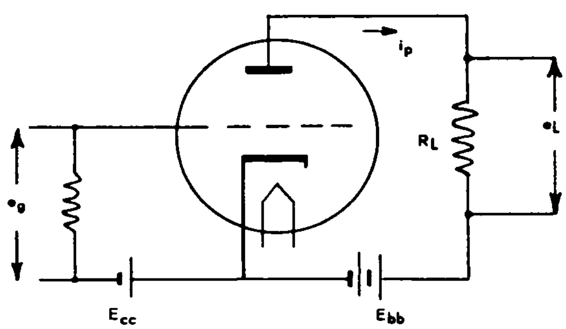


Figure 3-3. Triode Amplifier - Actual Connection.

Other Types of Electron Tubes - Many types of electron tubes other than the diode and the triode are used regularly in our business. The tetrode was developed to provide greater stability in amplifiers. The pentode was designed to provide a flatter characteristic than that of the tetrode. Beam power tubes, remote cutoff tubes, and special high-frequency tubes are used to fit different circuit requirements. Tubes are made in widely variant sizes and shapes in order to achieve particular characteristics. Gas-filled tubes, photosensitive tubes, cathode ray tubes, camera tubes, electron multipliers, velocity-modulated tubes and kinescopes are all special-service tube types which have become important in the communications industry. Our present aim is not to investigate the construction and exact characteristics of all these tube types; but rather to show how they may be used as building blocks in communication circuits.

Amplification

The Triode Amplifier - The triode as a circuit element has three important characteristics: the amplification factor, the plate resistance and the mutual conductance. The amplification factor can be shown to be numerically equal to the product of the plate resistance and the mutual conductance.

The amplification factor expresses the effectiveness of the grid as a control agent, compared to the effectiveness of the plate. Amplification factor is the ratio between a small plate voltage change and a grid voltage change which would produce an effect on the plate current of equal magnitude. The signs are opposite, for the grid must restore the change made by the plate if plate current is to remain unchanged during the measurement.

$$\text{Amplification Factor, } \mu = -\frac{de_p}{de_g} \text{ where } i_p \text{ is constant}$$

and de_p = small change in plate voltage

de_g = " " " grid "

i_p = plate current

The plate resistance, or more properly the dynamic plate resistance of a tube, is somewhat analogous to the internal resistance of a generator. It is defined as the ratio between a small plate voltage change and the corresponding plate current change (with grid voltage held constant).

$$\text{Plate Resistance, } r_p = \frac{de_p}{di_p} \text{ where } e_g \text{ is constant}$$

and di_p = small change in plate current

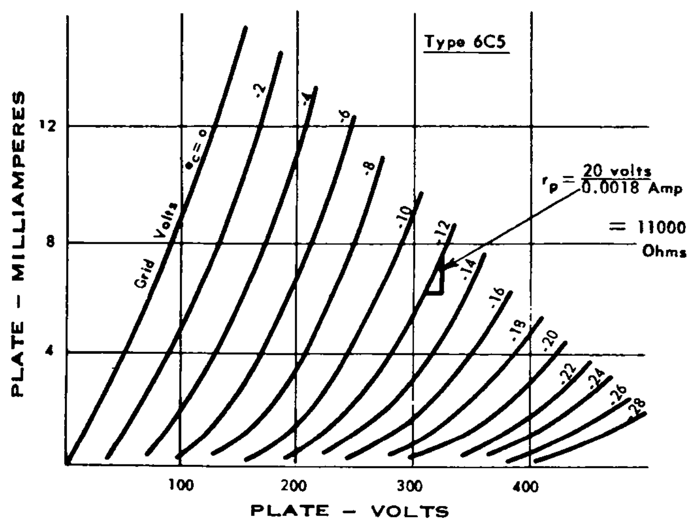


Figure 3-4. Triode Plate Characteristics.

Figure 3-4 shows a plot of triode plate characteristic curves and demonstrates the graphical method to find dynamic plate resistance for a certain operating point on one of the curves. It will be seen that the plate resistance is the inverse slope of the plate characteristic curve at the operating point.

The mutual conductance of a triode is the ratio of a small change in plate current to the small change in grid voltage which produces it, plate voltage remaining constant.

$$\text{Mutual Conductance, } g_m = \frac{di_p}{de_g} \text{ where } e_p \text{ is constant}$$

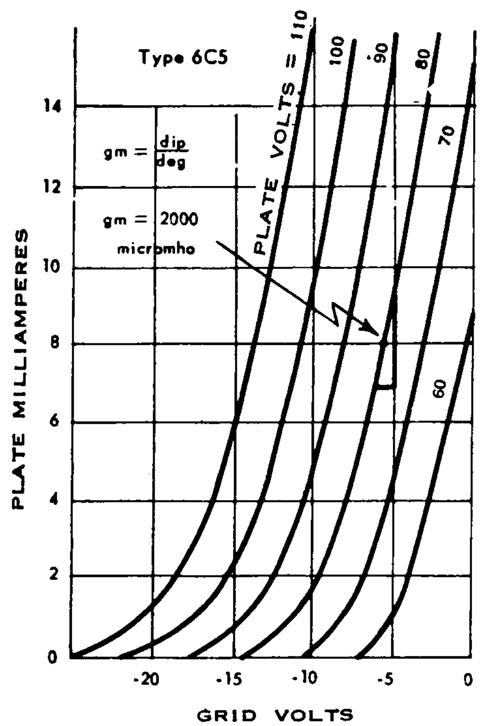


Figure 3-5. Triode Grid Characteristics.

Figure 3-5 shows a plot of triode grid characteristic curves and demonstrates the graphical method to find mutual conductance for a certain operating point on one of the curves. It will be seen that the mutual conductance is the slope of the grid characteristic curve at the operating point.

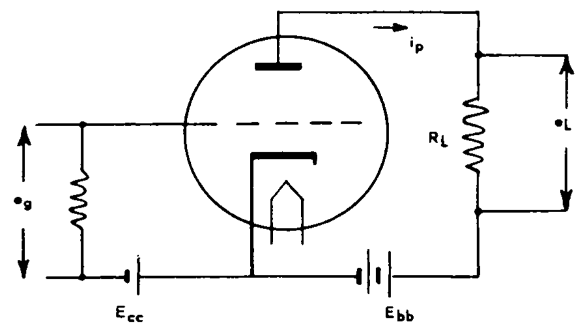


Figure 3-6. Triode Amplifier - Actual Connection.

Figure 3-6, which is identical with Figure 3-3, shows the actual connection of a triode amplifier. R_L is the plate load resistor and e_L is the voltage across the load. E_{bb} is the plate battery voltage and E_{cc} is the grid battery voltage. Figure 3-7 shows a simple equivalent circuit from which the performance of the amplifier is readily computed. From the equivalent circuit, Figure 3-7, it can be seen that the plate current is:

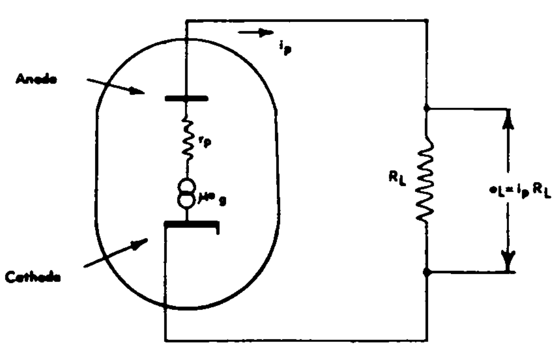


Figure 3-7. Triode Amplifier - Equivalent Circuit.

$$i_p = \frac{\mu e_g}{(r_p + R_L)}$$

and the useful amplification, $\frac{e_L}{e_g}$ is:

$$\text{Amplification} = \frac{\mu R_L}{(r_p + R_L)}$$

Multi-stage Amplifiers - Coupling - To obtain large power output from a small voltage source, it is necessary to use several stages of amplification with the output of one stage feeding the input of the next. Transfomer coupling is sometimes used in multi-stage audio amplifiers. The transformer provides a simple method to isolate the dc plate voltage from the grid of the following tube. The alternating (signal) voltage on the plate is reproduced in the secondary transformer winding and the voltage may be stepped up by providing more turns on the secondary than on the primary winding. The transformer may also be designed to match a low-impedance load to a high impedance source. Figure 3-8 shows two stages of an amplifier with transformer coupling.

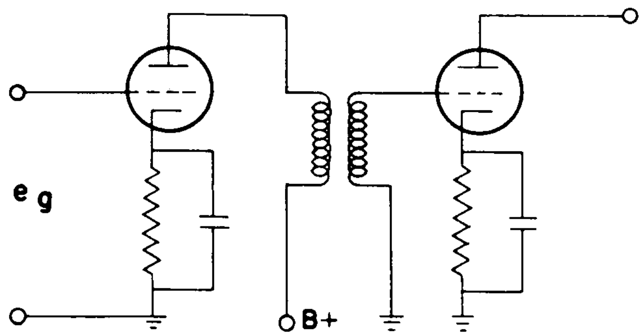
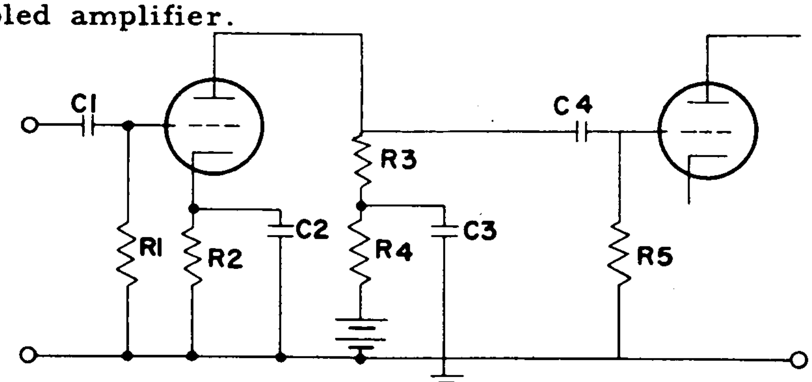


Figure 3-8. Transformer-Coupled Amplifier.

Resistance-capacitance coupling is another widely used method to connect amplifier stages. Resistance-capacitance coupled amplifiers are relatively cheap and have good fidelity over comparatively wide frequency ranges. Figure 3-9 shows an RC-coupled triode amplifier and gives the names of the circuit elements.

Impedance coupling is obtained by replacing the load resistor of an RC-coupled amplifier with an inductance. See Figure 3-10. An impedance-coupled amplifier can be designed to give fairly uniform frequency response over a limited frequency range. In such case the amplification is greater than for a similar RC-coupled amplifier.



R1 GRID—LEAK RESISTOR
R2 CATHODE BIAS RESISTOR
R3 PLATE LOAD RESISTOR
R4 PLATE DECOUPLING RESISTOR
R5 SECOND STAGE GRID RESISTOR
C1 INPUT COUPLING CAPACITOR
C2 CATHODE BYPASS CAPACITOR
C3 PLATE SUPPLY BYPASS CAPACITOR
C4 OUTPUT COUPLING CAPACITOR

Figure 3-9. RC-Coupled Amplifier.

In a direct-coupled amplifier, the plate of one tube is connected directly to the grid of the next tube. With direct coupling, it is necessary to provide separate power supplies for each stage or to use a special voltage-divider. Figure 3-11 shows direct coupling with a voltage divider network.

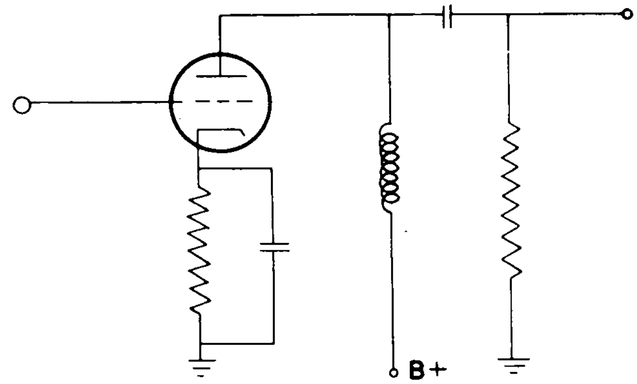


Figure 3-10. Impedance-Coupled Amplifier.

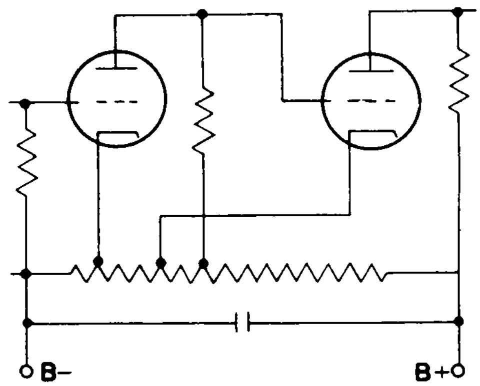


Figure 3-11. Direct-Coupled Amplifier.

Band Width Requirements - An important characteristic of an amplifier is its band width. In general, the greater the band width the less the gain which may be obtained. Single-frequency amplifiers are used to amplify carriers or signalling tones. Audio amplifiers may have band width requirements of 5,000 to 15,000 cycles. Video amplifiers must have band width of several megacycles.

Class A, B, C, Amplifiers - Amplifiers are classed according to the method of operation. The dc grid bias and the input signal of an oscillator may be adjusted so that plate current flows at all times or so that plate current flows only during part of each cycle of the signal.

A Class A amplifier is one in which plate current flows at all times.

A Class B amplifier is one in which grid bias is adjusted so that plate current is approximately zero in the absence of a signal and plate current flows for approximately one-half of each cycle when a signal is applied.

A Class C amplifier is one in which the grid bias is adjusted appreciably beyond the cutoff value, so that plate current flows for appreciably less than half of each cycle when a signal is applied.

Class A amplifiers give faithful reproduction of the input signal and are widely used for audio amplification and modulated carrier amplification. Class B amplifiers when used for audio amplification must be used in push-pull. Class C amplifiers can be used only for unmodulated rf waves.

Cathode Follower - Figure 3-12 shows the circuit of a cathode follower. The output is taken across the cathode resistor. The cathode "follows" the grid-input voltage in that it has the same polarity. The cathode follower is a valuable impedance-matching device. It has always less than unity voltage gain, but may produce a power gain.

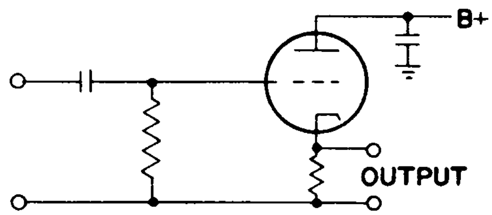


Figure 3-12. Cathode Follower

Feedback - Feedback is the application of a portion of the output of a tube to the input of the same tube. Positive feedback, i.e., feedback which adds to the input signal, is used to provide increased gain or oscillation. Negative feedback, feedback phased to cancel a portion of the input signal, is used to increase stability and to decrease distortion. Negative (inverse) feedback is often applied to more than one stage; that is, part of the output of a stage is fed back to the input of a preceding stage.

Oscillation

Tank Circuit - Figure 3-13 illustrates the operation of a tank circuit which is composed of a condenser and a coil. If the switch is closed toward the battery, the condenser will be charged to the battery potential. If the switch is then thrown, the condenser will discharge through the coil and, because of the inertia effect of the coil, current will flow until the condenser is charged to the opposite polarity. The current will then reverse and the procedure will continue. The charge on the condenser will be slightly smaller with each alternation because of circuit losses. The damped oscillation which results will have a frequency which depends on the inductance and the capacity of the coil and the condenser.

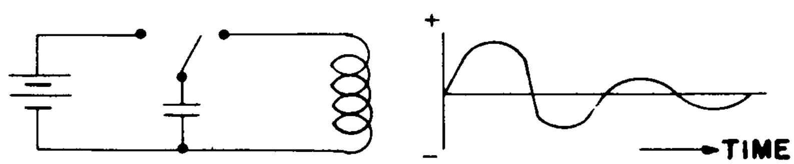


Figure 3-13. Tank Circuit

Simple Oscillator - Suppose that a tank circuit is placed in the plate circuit of an amplifier. If small impulses are fed into the grid at the right time to overcome the losses of the tank circuit, then instead of a damped oscillation a continuous oscillation will result. The impulses may be supplied to the grid by positive feedback. The frequency of oscillation will be:

$$f = \frac{1}{2\pi \sqrt{LC}}$$

Types of Oscillators - Figure 3-14 shows an oscillator which obtains feedback by a "tickler" coil. Figure 3-15 shows a series-fed Hartley oscillator and Figure 3-16 shows a shunt-fed Hartley oscillator (one in which the dc path does not go through the coil). The Colpitts oscillator is a similar circuit except that the coil is not tapped. Instead, the cathode is connected to the mid-point of two condensers which replace the single condenser of the Hartley circuit.

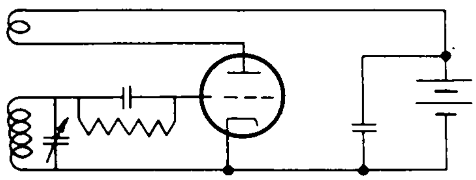


Figure 3-14. Tickler Coil Oscillator.

The tuned-plate, tuned-grid oscillator has parallel resonant circuits in both plate and grid. It depends on the interelectrode capacity of the tube for feedback.

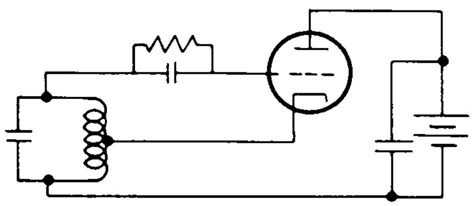


Figure 3-15. Series-Fed Hartley.

The crystal-controlled oscillator uses the same circuit as the tuned-plate, tuned-grid oscillator. Crystal-controlled oscillators can provide very good frequency stability.

The phase-shift oscillator has a series of RC networks in the plate to provide the proper phase for feedback.

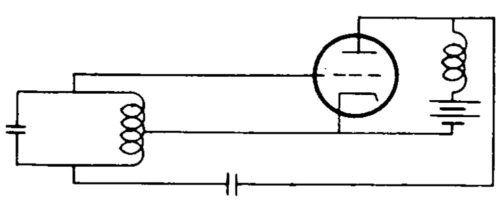


Figure 3-16. Shunt-Fed Hartley.

The beat oscillator is a type which is widely used in test instruments to provide a widely variable frequency output. The glow tube relaxation oscillator is used to provide oscillations which are rich in harmonics.

At ultra-high frequencies, special tubes must be used because the transit time of electrons from cathode to anode becomes an important part of the period of the oscillation. UHF tubes are built with very close-spaced electrodes. At still higher frequencies, positive-grid oscillators, klystrons, magnetrons, and travelling-wave tubes are used.

Modulation and Demodulation

Carrier frequencies are chosen for their propagation characteristics and are assigned in such manner as to avoid interference between circuits. Modulation is the process of varying some characteristic (e.g. amplitude, frequency, phase) of a carrier wave in accordance with the variations of a signal wave of lower frequency. The modulated wave may then be transmitted and demodulated at the receiving end of the circuit to reproduce the modulating wave. In carrier telephony, several messages (each having the same frequency range of perhaps 250 to 3,500 cycles) may be "stacked up" one above the other in the frequency spectrum by the use of carriers of proper frequencies. All the messages may then be transmitted simultaneously over a single wide band circuit. At the receiving end, the modulated carriers are separated and each is demodulated to reproduce the several messages.

Amplitude Modulation - In amplitude modulation, the amplitude of the carrier wave is varied by the modulating wave. If the carrier magnitude is varied to such an extent that the minimum value is zero and the maximum value is twice the unmodulated magnitude, 100 per cent modulation is obtained. Modulation beyond the 100 per cent point, called overmodulation, produces distortion.

Many circuits have been designed to accomplish the process of modulation. The modulating voltage may be applied in either the grid circuit or the plate circuit of a triode. In tetrodes and pentodes, the screen grid and suppressor grid may be employed. Networks of varistors are widely used as modulators in carrier systems.

Sidebands - It can be shown that the complex wave form of an amplitude-modulated (AM) carrier is really made up of the carrier frequency, upper sideband frequencies, and lower sideband frequencies. In the simple case of a single-frequency modulating wave, the upper and lower sidebands will be each a single frequency and will have frequencies of carrier frequency plus modulating frequency and carrier frequency minus modulating frequency respectively (see Figure 3-17). The components of an amplitude-modulated carrier may be separated by filters. Because each sideband contains all the information of the modulating wave, it is possible to suppress the carrier and transmit only a

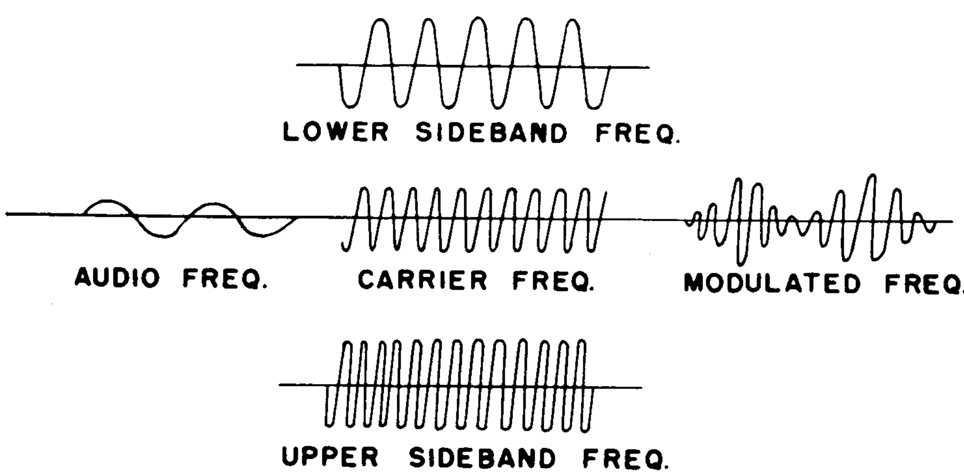


Figure 3-17. Amplitude Modulation With Single-Frequency Tone.

single sideband. Single-sideband, suppressed carrier transmission is popular because of its economy of band width.

AM Detection (Demodulation) - Figure 3-18 shows the circuit of a diode detector. The output of the diode contains a dc component which does not change with modulation, but which is a measure of the carrier strength.

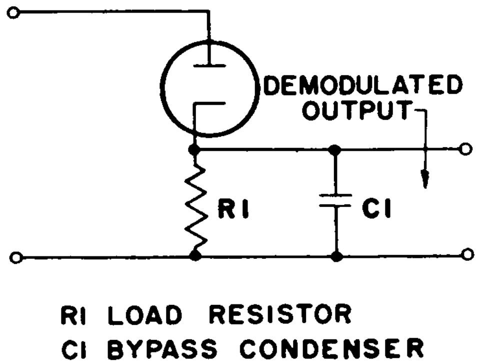


Figure 3-18. Diode Detector.

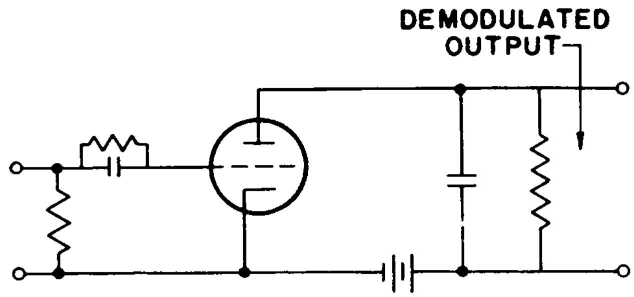


Figure 3-19. Grid Leak Detector.

The grid-leak detector of Figure 3-19 is equivalent to a diode detector and an amplifier.

Frequency Modulation - Figure 3-20 illustrates frequency modulation of a carrier wave.

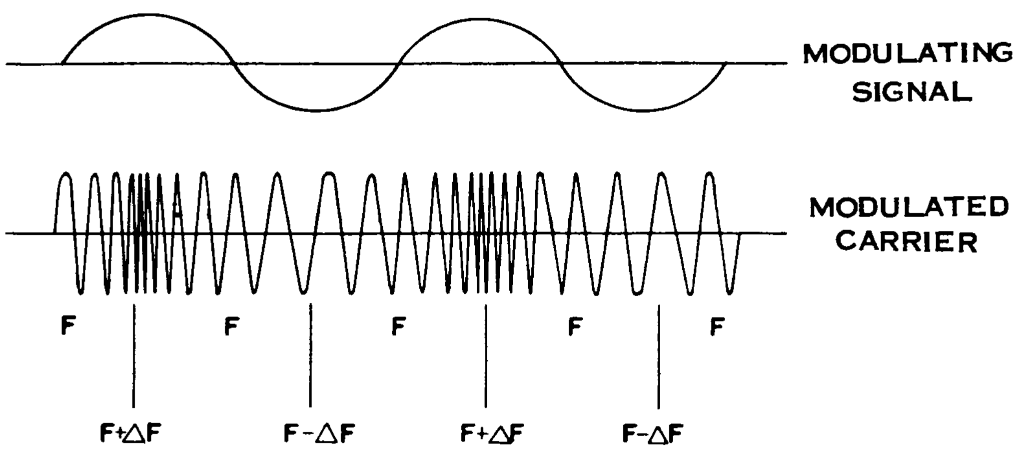


Figure 3-20. Frequency Modulation With Single-Frequency Tone.

The three following statements are descriptive of a carrier wave which has been frequency modulated:

a. The amplitude of the carrier remains constant as the carrier frequency is varied by modulation.

b. Deviation (i.e., frequency swing) is proportional to the amplitude of the modulating wave.

c. The rate of frequency change is proportional to both the amplitude and the frequency of the modulating wave.

FM Modulation Methods - Various schemes may be used to produce frequency modulation. A simple (but inefficient) method is to use a condenser microphone in an oscillator tuning circuit. In this case, sound waves will vary the capacity of the microphone and the oscillator frequency will vary in direct relation to the amplitude of the sound waves.

Another, and better method for frequency modulation utilizes a reactance tube. By means of a suitable circuit, a tube may be caused to act like a reactance (coil or condenser) and its reactance may be varied in accordance with a signal applied to its grid. If such a reactance tube is connected in parallel with the tank circuit of an oscillator, the frequency of the oscillator will vary in direct relation to the amplitude variations of the signal applied to the reactance tube.

Still another method, the phase-shift method, is to use a phase splitter to feed the carrier with equal magnitude, but with a 90-degree phase difference, to the control grids of two paralleled amplifiers. The modulating signal is then fed to another grid of the tubes in push-pull. In the paralleled plate outputs of the two tubes the resultant voltage then varies in phase in accordance with the modulating voltage. (This is phase modulation, but may be converted to FM by pre-distorting the modulating signal.)

FM Detection - Figure 3-21 shows a block diagram of a typical FM receiver. In such a receiver the modulated carrier is first amplified, then

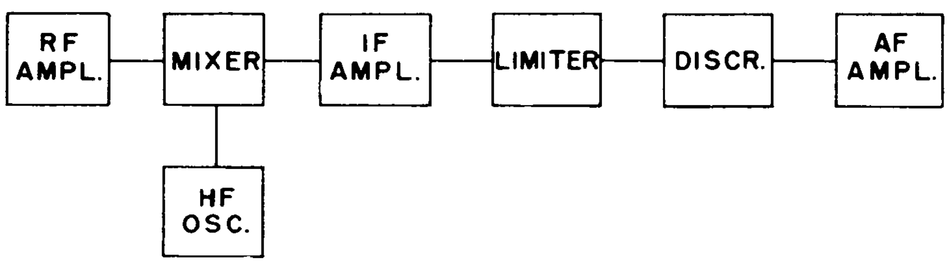


Figure 3-21. Typical FM Receiver.

beat down by combination with an oscillator frequency in a mixer stage which has its plate tuned to the difference of the carrier frequency and the oscillator frequency. The intermediate frequency which results is then amplified and fed to a limiter. The limiter, which is a grid-leak biased amplifier with low plate and screen voltage, limits negative peaks by cutoff and limits positive peaks by grid action (not by plate saturation). The output of the limiter is constant-amplitude FM which is fed to a discriminator. The discriminator (FM detector) has zero output, both ac and dc, if the carrier is unmodulated and is exactly on the receiver frequency. If the carrier is modulated, the discriminator has an ac output equivalent to the modulating signal.

Pulse Modulation - The modulation schemes described on the preceding page produce a continuous wave of energy. Pulse modulated systems transmit carrier in a series of short bursts or pulses. In the intervening periods, no energy is passed.

This method depends on the fact that any signal wave-shape can be completely defined by taking essentially instantaneous samples of its amplitude at regularly spaced successive intervals of time — provided that at least two samplings are made in each cycle of the highest frequency included in the signal.

There are several ways in which the signal sampling information can be incorporated in the carrier pulses. Three are illustrated in Figure 3-22.

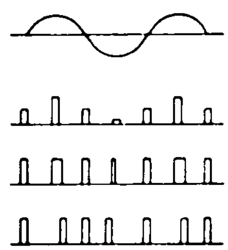


Figure 3-22. Pulse Modulation Methods.

In pulse-amplitude modulation, the pulses are of uniform time duration, but vary in amplitude in accordance with the signal amplitude at the instants of sampling. In pulse-width modulation and pulse-position modulation, the pulses are of constant amplitude. Pulse-width modulation varies the duration or width of each pulse in proportion to the amplitude of the modulating signal when each sample is taken. While in pulse-position modulation, all pulses are of the same duration but are displaced with respect to a uniform time scale — the amount of displacement being determined by the amplitude of the signal at sampling.

Although these modulating techniques have found limited application in telephone practice up to this time, they have several advantages. The transmitter has a low average power consumption compared to the possible signal to noise ratio during each pulse. The latter two schemes permit the use of limiters in the receiver, thereby insuring excellent discrimination against noise. Moreover, it is possible to transmit a number of separate signals over a single carrier by means of time-division multiplexing, or interleaving the time scales of the several channels. Their principal disadvantage is the relatively wide frequency band required to pass the sharp pulses.

Rectification

Half-wave Rectifier - Because it will pass current in only one direction, a single diode may be used as a half-wave rectifier as shown in

Figure 3-23. It will be seen that an ac input produces a dc output which pulsates at the input frequency.

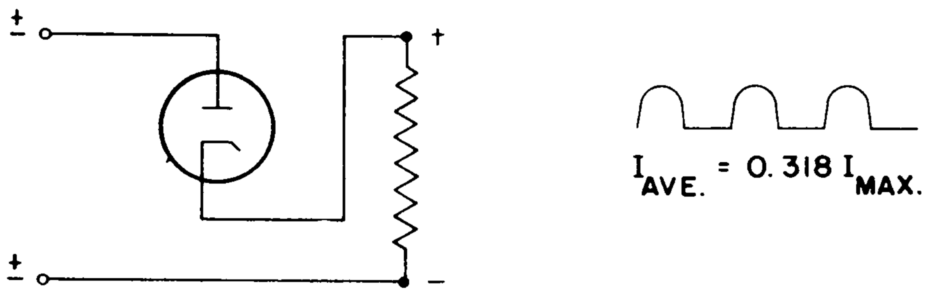


Figure 3-23. Half-Wave Rectifier.

Full-wave Rectifier - Figure 3-24 shows a center-tapped transformer used with two diodes to make a full-wave rectifier with a dc output which

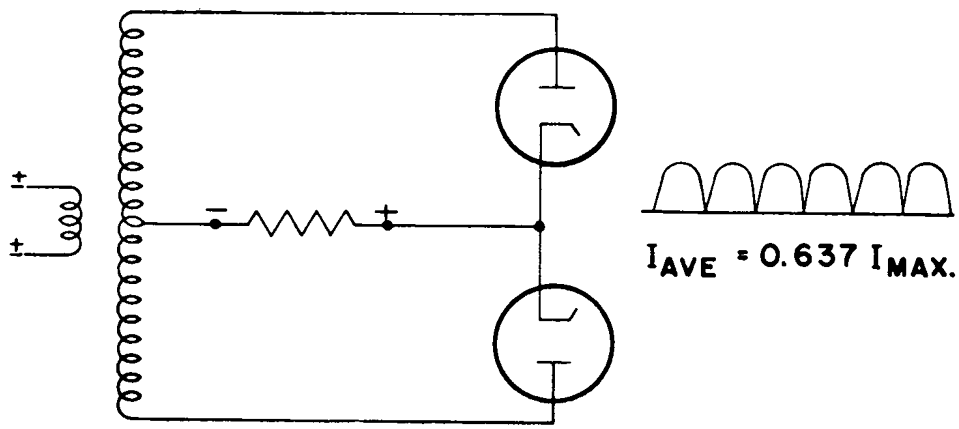


Figure 3-24. Full-Wave Rectifier With Center-Tapped Transformer.

pulsates at twice the input frequency. Figure 3-25 shows how a bridge circuit, which does not require a center-tapped transformer, can also be used as a full-wave rectifier. Vacuum diodes, gas-filled diodes, or metallic rectifiers may be used in such a circuit.

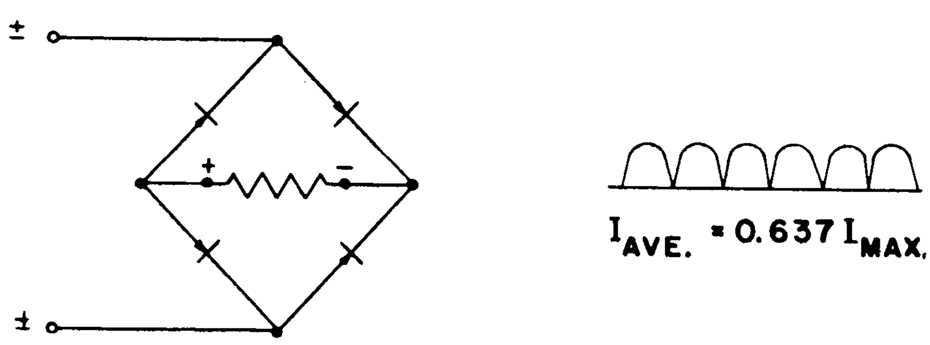


Figure 3-25. Bridge Circuit.

Ripple Filters - To smooth out the pulsating dc output of rectifiers, ripple filters are employed such as the choke-input filter of Figure 3-26 or

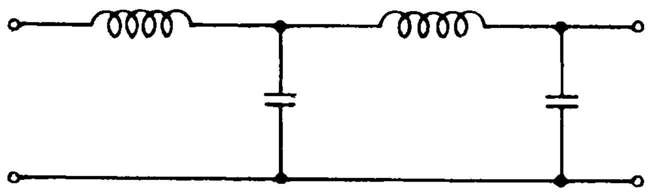


Figure 3-26. Choke-Input Filter.

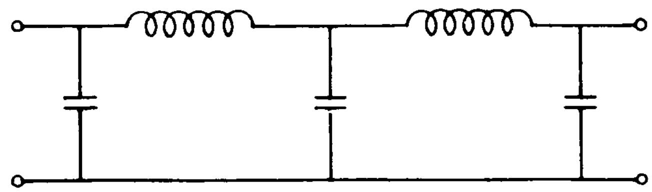


Figure 3-27. Condenser-Input Filter.

the condenser-input filter of Figure 3-27. In general, the condenser-input filter is used only with high-vacuum type tubes. The choke-input filter may be used with either high-vacuum or gas-filled tubes.

Semi-Conductors

Semi-conductors are crystalline materials which have electrical properties intermediate between those of conductors and those of insulators. Examples of semi-conductors which are useful at the present time are germanium, silicon, copper oxide, cadmium sulphide, lead sulphide, and selenium.

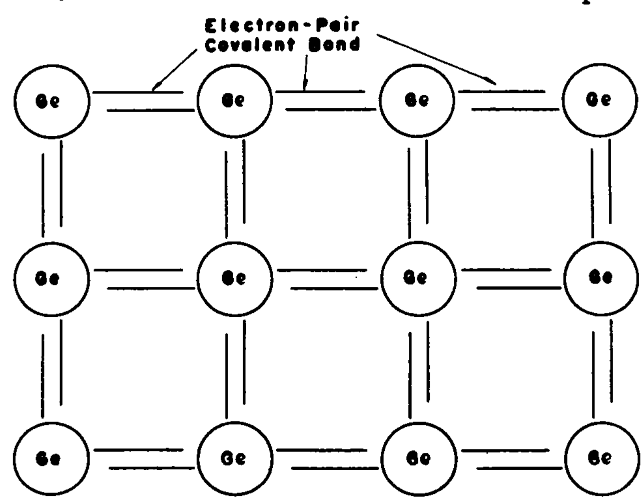


Figure 3-28. Pure Germanium in Crystal Form.

Germanium - Germanium (atomic number 32, atomic weight 72.60) has four outer, or valence-ring electrons. For discussion of conduction theory the other 28 electrons, which are tightly bound in the inner rings, may be ignored. In crystalline germanium in a pure state, each valence-ring electron coordinates its motion with that of corresponding valence-ring electrons of neighboring atoms. We say that co-valent bonds, or electron pairs are formed. See Figure 3-28. In this state, all electrons are tightly bound and the germanium is an insulator.

However, the addition of a slight amount of properly chosen impurity will change the germanium to a semi-conductor. Suppose, for instance, that a minute quantity of arsenic (which is pentavalent) is added. Co-valent bonds will be formed between the arsenic atoms and the adjacent germanium atoms, but for each arsenic atom added there will be one electron left over. The arsenic atom is called a donor atom and the germanium with the excess of electrons is called N-type germanium (N for Negative). See Figure 3-29.

If, on the other hand, a controlled quantity of indium (which is trivalent) is added to pure germanium, co-valent bonds will again be formed between impurity atoms and germanium atoms; but this time each impurity atom will have one electron too few and there will be holes where ideally electrons should be present. The indium atom is called an acceptor atom and the germanium with the holes, i.e. missing negative charges, is called P-type germanium (P for Positive). See Figure 3-30.

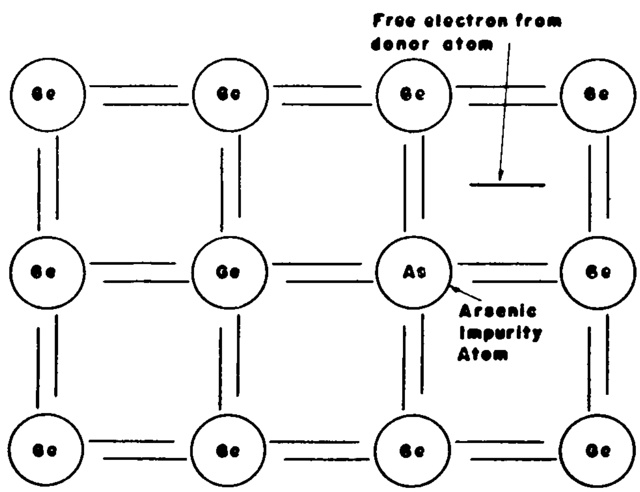


Figure 3-29. N-Type Germanium.

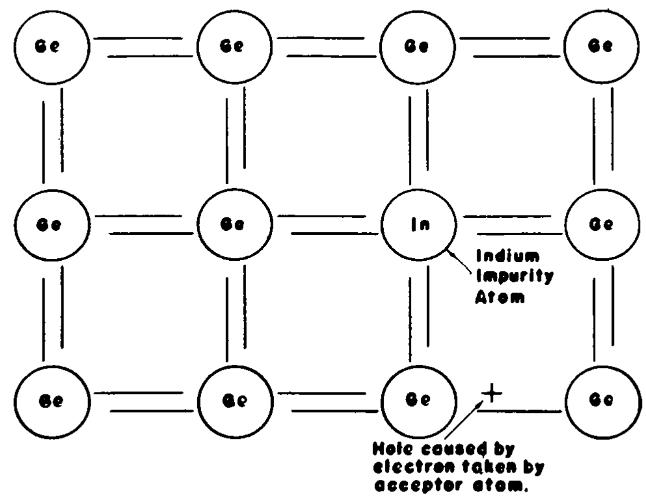


Figure 3-30. P-Type Germanium.

The concentration of impurity atoms in semi-conductor germanium is very low:

A ratio of one to 100 million is good.

A ratio of one to 10 million is too rich.

P-N Junctions - It should be noted that P-N junctions are not slabs of N-type and P-type germanium put together. A grown junction is formed by adding acceptor and donor impurities at the right times during formation of a single crystal. A diffused junction is made by placing a pellet of impurity on one face of a wafer of semi-conductor germanium and then heating to the melting point of the impurity. Under proper conditions, some of the impurity atoms will diffuse a short distance into the wafer. In the point-contact junction, a fine, pointed wire makes pressure contact with the face of a semi-conductor germanium wafer. After assembly, a high-current surge is used to "form" the device. The heat generated by the surge converts a small spot under the point contact from N-type to P-type germanium (or vice versa). Figure 3-31 shows three types of P-N junctions.

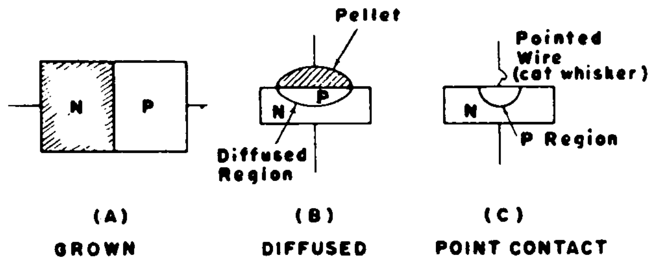
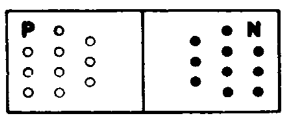


Figure 3-31. P-N Junctions

In a P-N junction at equilibrium, the holes and electrons concentrate away from the junction. See Figure 3-32. The junction forms a barrier to the flow of holes and electrons and is sometimes called an electron hill.



○ Hole
● Electron

Figure 3-32. P-N Junction at Equilibrium.

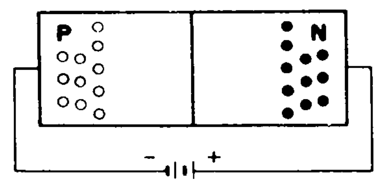


Figure 3-33. P-N Junction with Reverse Bias.

A battery connected as in Figure 3-33 provides reverse bias and tends to concentrate the holes and electrons further away from the junction. It therefore increases the potential hill. However, a battery connected as in Figure 3-34A provides forward bias and thereby reduces the potential hill so that current may flow by a combination of electron carriers and hole carriers as shown in Figure 3-34B.

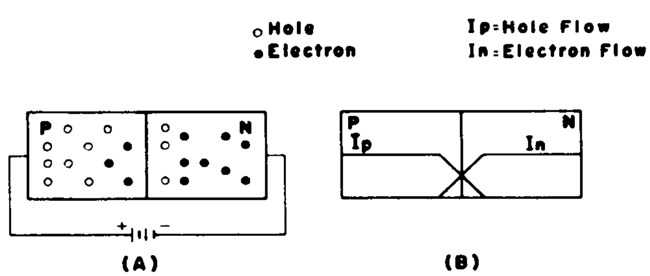


Figure 3-34. P-N Junction with Forward Bias.

It will be seen that a P-N junction passes current more readily in one direction than in the other. It is, then, a rectifier and is called a semi-conductor diode or crystal rectifier. Such diode rectifiers have been widely used as first and second detectors in radio, television and microwave circuits for several years. An example of a point-contact germanium diode is the 1N23B crystal which is used in our TE microwave equipment.

N-P-N Junction Transistors - The N-P-N junction transistor of Figure 3-35 may be considered to be the equivalent of two germanium crystals combined, with the P-type section made common. The middle section of this transistor is made very thin and the electrodes are all soldered to their respective sections to give low-resistance contact. The emitter has forward bias for high conductivity, the collector has reverse bias for low conductivity, and the base connects to the common P-type area.

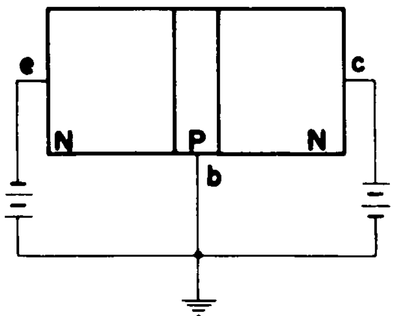


Figure 3-35. N-P-N Junction Transistor.

In the N-P-N junction transistor, the negative potential of the emitter pushes electrons toward the first junction. Some electrons cross the first barrier, or potential hill, to the P-type base region. A few electrons combine with holes in this region, but most of them pass through the narrow base region and are accelerated by the second potential hill into the N-type collector region. In the N region they are attracted to the positive collector. The collector current is less than the emitter current because of the recombination of holes and electrons in the base region. Therefore, the current gain, alpha, is less than unity:

$$a = i_c / i_e = 0.95 \text{ is typical value}$$

However, collector resistance is higher than emitter resistance, typical values being one megohm vs. 500 ohms. Resistance gain, then, is:

$$r_o / r_i = 1{,}000{,}000/500 = 2000$$

and voltage gain in the same typical case is 1900:

$$VG = i_c r_o / i_e r_i = a(r_o / r_i) = 1900.$$

Power gain, which depends on the square of the current, is:

$$PG = a^2 (r_o / r_i) = 1805$$

P-N-P Junction Transistors - The operation of the P-N-P junction transistor of Figure 3-36 may be explained in the same manner as that of the N-P-N transistor, provided that we speak of hole conduction instead of electron conduction. Battery connections are, of course, reversed and the holes are considered to be positive carriers.

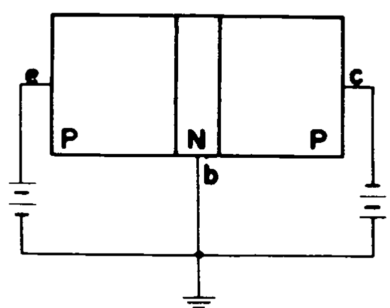


Figure 3-36. P-N-P Junction Transistor.

Point-Contact Transistors - The point-contact transistor, shown in Figure 3-37, is usually formed from an N-type wafer of germanium. In manufacture, a momentary heavy surge of current through the "cat-whiskers" causes

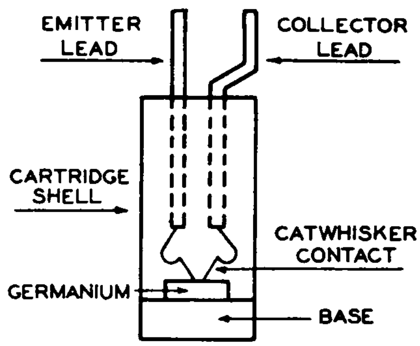


Figure 3-37. Point-Contact Transistor.

enough heat to form small P-type areas under the point contacts. We then have a special form of P-N-P junction. The close spacing of the electrodes and the high-intensity field achieved by the use of point-contacts permits holes injected by the emitter to have relatively large effect on collector current. Alpha, the current gain, is therefore greater than unity in the point-contact transistor. A typical value is:

$$a = i_c / i_e = 2.5$$

Because input resistance is about 300 ohms and output resistance perhaps 20,000 ohms, the voltage gain for the typical point contact transistor becomes:

$$VG = a\,(r_o / r_i) = 167$$

and the power gain:

$$PG = a^2 (r_o / r_i) = 419$$

P-N-P-N Junction Transistors - The P-N-P-N junction transistor also gives greater-than-unity current gain. Such a transistor is shown in Figure 3-38.

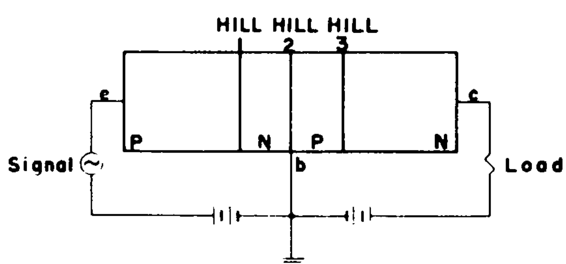


Figure 3-38. P-N-P-N Transistor.

In this transistor, holes move from the emitter toward the collector; but they are trapped by the third potential hill. The space-charge effect of the holes at this third junction reduces the barrier to collector current. Electrons from the collector end then flow into the P region and, with the aid of potential hill number two, move on to the N region and flow to the base. Because of the space-charge effect at the third junction, alpha may reach twenty.

Transistor Tetrodes - An N-P-N junction transistor with a fourth electrode, designated B_2 in Figure 3-39, is called a transistor tetrode.

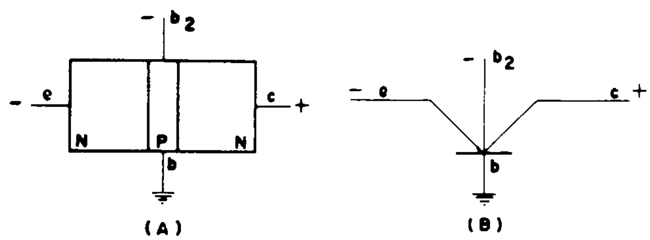


Figure 3-39. Transistor Tetrode.

In a conventional transistor, high-frequency cutoff is inversely proportional to: (1) base resistance, (2) the square of the base layer thickness, and (3) the collector capacitance. In order to increase the high-frequency cutoff figure in the transistor tetrode a very thin P layer is used, the collector junction area is reduced, and a negative bias of about minus six volts is applied to B_2 to confine transistor action to the portion near the base electrode. In a typical case, the application of the bias to B_2 has the following effect:

a. reduces R_B from 1000 ohms to 40 ohms.
b. negligible change in R_E.
c. reduces R_C from 3.0 megohm to 1.5 megohm.
d. reduces alpha from 0.95 to 0.75.
e. increases cutoff frequency from 0.5 MC to 1.5 MC.

Thus, it is seen that increased band width is achieved at the expense of gain.

Surface-Barrier Transistors - The surface-barrier transistor, Figure 3-40, is somewhat similar to the P-N-P junction transistor in appearance, but contains only one type of germanium.

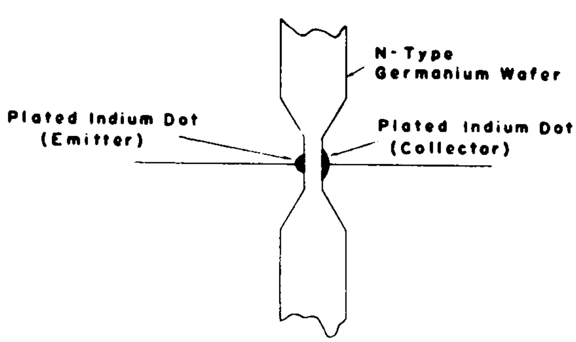


Figure 3-40. Surface-Barrier Transistor.

By an ingenious manufacturing process, a portion of a germanium wafer is electrolytically eroded to an extremely thin cross section by two fine jets of indium sulphate. The thickness can be controlled within a few millionths of an inch. When the proper thickness has been reached, the current through the electrolyte is reversed and emitter and collector electrodes of indium are plated on the thin section without any interruption of the twin jets. In this way contamination of the plating surfaces by the atmosphere is avoided. The indium does not diffuse into the germanium, but beneath each electrode, a barrier layer of pure germanium about 1/10,000 inch thick is formed. This layer contains almost no free electrons or holes.

Photo Transistor - The photo transistor, pictured in Figure 3-41, is characterized by a retainer to collector resistance which varies with the intensity of the light falling on the germanium wafer.

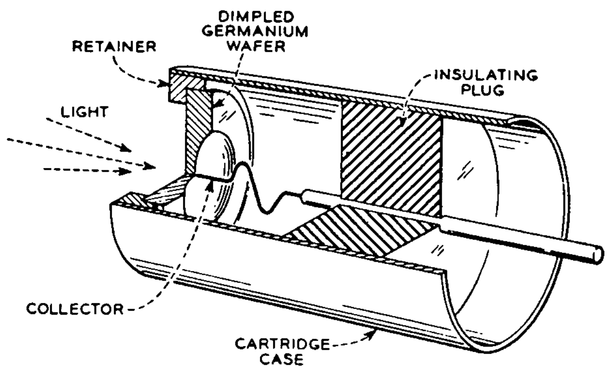


Figure 3-41. The Photo Transistor.

Transistors can perform many functions of vacuum tubes, such as: amplification, oscillation, and detection. Among the advantages of transistors, as compared to vacuum tubes are:

a. No vacuum required.
b. No filament (no filament power, no warm-up time).
c. Small size.
d. Light weight.
e. No heat dissipation problem.
f. Extremely rugged (shock and vibration).
g. Long life.

Present disadvantages are:

a. Limited power-handling capability.
b. Close manufacturing tolerances required.
c. Poor performance at high temperatures.

CHAPTER 4

UNITS OF MEASUREMENT AND RATING SYSTEMS

The ideal telephone connection would simulate the transmission conditions existing when two customers converse face to face. But every circuit tends to deliver a signal which differs in some respects from the signal impressed at its input. Determining objectives which are a realistic approximation of the ideal, designing circuits that will meet the objectives, confirming that circuits are operating as designed, all require yardsticks for measuring transmission performance.

UNITS OF TRANSMISSION MEASUREMENT

The technical term which occurs most frequently in the vocabulary of transmission people today is undoubtedly "decibel" or its abbreviation "db". However, there are older units which are still encountered occasionally, and there are several other units with specialized applications.

Voltage, current, and power in a communication circuit can be measured in volts, amperes, and watts as in any other electrical system. The values to be measured in practice are frequently small compared to these units, making it more convenient to use their submultiples:

millivolt or one thousandth of a volt,
milliampere or one thousandth of an ampere,
milliwatt or one thousandth of a watt.

These units are well suited for defining the electrical conditions at a point in a circuit, but when we wish to compare the conditions in two circuits, or at two points in the same circuit, they lead to complications. Suppose that the power entering a network is two milliwatts and that leaving it is one milliwatt. We can describe the transmission loss of the network by saying that it reduces the power by a ratio of 1/2 or 0.5. Two such networks in tandem would reduce the power by a ratio of (0.5 x 0.5) or 0.25. This is simple enough, but suppose we are concerned with a circuit which reduces the power by a ratio of 0.537 in each mile and is 9.7 miles long. Our problem then is to multiply 0.537 by 0.537, 9.7 times. Such a computation is possible, and if the input to the circuit were one milliwatt the output would be 0.0024 milliwatts. But obviously we need a more convenient way of describing transmission loss than the simple ratio of input and output power.

The Decibel

In this country the accepted practical unit for comparing two signals is the decibel (db). The signals compared are usually electrical, but may be acoustic or even waves of other forms of energy. The decibel is defined by the equation

$$N = -10 \log_{10} \frac{P_2}{P_1}$$

Where N is the number of decibels and P_1 and P_2 are the powers of the two signals compared. If P_1 and P_2 are the powers at two points in the same circuit, P_1 is at the earlier and P_2 at the later point encountered in the direction of propagation of the signal. When there is a loss of power between the two points (P_1 is greater than P_2), N will be positive. On the other hand, if there is an amplifier in the circuit and P_2 is greater than P_1, N will be negative. Therefore, a transmission gain is a negative loss when expressed in decibels.

Expressed in words, the equation says, "the number of db relating two powers is equal to minus ten times the common logarithm of the ratio of the two powers". A detailed description of logarithms is not pertinent to this discussion. But stated briefly, for every number greater than zero, there is another number called its logarithm. The logarithm is the power to which a "base" must be raised in order to equal the number corresponding to the logarithm. There are two systems of logarithms. The one used to define the decibel is known as the common or Brigg's system. It uses a base of 10. The other, known as natural or Napierian logarithms uses a base of ε or 2.7183. This second system is used to define another transmission unit which we shall discuss shortly.

Logarithms have a peculiar property — adding the logarithms of two numbers is equivalent to multiplying the two numbers. This fact is one of the principal reasons for defining the db in terms of logarithms. It permits us to sidestep the difficulty we enountered above in trying to work with transmission losses in terms of simple power ratios. When losses and gains are expressed in decibels, the net loss of the several circuits connected together can be determined by algebraic addition. The network which reduced the power by a ratio of 1/2 would have a loss of 3 db. Two such networks in tandem would have a loss of (3 + 3) or 6 db. The circuit that reduced the power transmitted by a ratio of 0.537 in each mile would have a loss of 2.7 db per mile, and (2.7 x 9.7) or 26.2 db in 9.7 miles.

Logarithms can be readily determined from standard mathematical tables, and these tables are usually accompanied by instructions for their use. In practice it is rarely necessary to compute decibles with mathematical tables. Virtually all of our measuring equipment is calibrated directly in db, and the losses of all standard facilities are tabulated in db in the practices.

The practices also contain tables directly relating db and power ratio. An abbreviated table is reproduced here.

APPROXIMATE POWER RATIO

	For Losses		For Gains
Decibels	Decimal	Fractional	Decimal
0	1.000	1	1.000
1	.794	4/5	1.259
2	.631	2/3	1.585
3	.501	1/2	1.995
4	.398	2/5	2.512
5	.316	1/3	3.162
6	.251	1/4	3.981
7	.200	1/5	5.012
8	.158	1/6	6.310
9	.126	1/8	7.943
10	.100	1/10	10.00
20	.010	1/100	100.00
30	.001	1/1000	1000.00

NOTE: To express corresponding voltage, current, or sound pressure ratios in db, multiply figures in "Decibels" column by 2.

From the table, it may be seen that a gain of 10 db results in a new power value 10 times the original level. Each 10 db gain multiplies the power by 10, thus a gain of 30 db equals 1 x 10 x 10 x 10 or 1000. A 30 db loss will be 1 ÷ 10 ÷ 10 ÷ 10 which equals 0.001.

The ratio for any number of decibles in gain or loss can be readily determined by merely adding up the decibels required to equal the specific value and then multiplying the corresponding decimals. For example, to determine the ratio corresponding to 11 db loss, the decimals 0.100 (for 10 db) and 0.794 (for 1 db) are multiplied, giving a power ratio of 0.079; for 11 db gain, the decimals 10.00 (for 10 db) and 1.259 (for 1 db) are multipled, giving a power ratio of 12.59.

It is frequently more convenient to measure or compute the voltage of a signal or its current. Then our equation for the decibel becomes

$$N = -20 \log_{10} \frac{E_2}{E_1} = -20 \log_{10} \frac{I_2}{I_1}$$

These definitions have one limitation; the circuit impedances at the two points must be the same. The abbreviated db table shows power ratios only. Since the definitions of the db in terms of power and voltage or current ratios differ only by a factor of two, this table can also be used for voltage and current ratios by multiplying each figure in the decibel column by 2. For instance, a power loss ratio of 1/2 is 3 db, so a voltage loss ratio of 1/2 would be 6 db.

The decibel is a relative unit and always involves the ratio of two powers. It is improper to use the decibel in an absolute sense as, for instance, to say that a certain signal has a level of so many db, unless there is stated, or clearly understood, a reference power with which the signal power is being compared. The decibel is not restricted to expressing only transmission losses and gains. The reference power may be the power of the same signal at another point in the circuit, as in the preceding discussion; it may be the power of the same signal at the same point under a different condition (such as when preceding equipment is omitted from the circuit); it may be the power of a different signal in the same or another circuit; or it may be an arbitrarily chosen value of power, such as one milliwatt. Thus, the following statements are proper:

"The transmission loss between points A and B is 10 db."

"The level at point B is 10 db lower than at point A."

"The loss due to adding a coil between points B and C is 0.5 db."

"The level at point B is 15 db below one milliwatt."

"The noise at the circuit terminal is 31 db below the signal."

A more common expression for the last statement is that, "The signal-to-noise ratio at the circuit terminal is 31 db."

One db represents about the least difference in loudness in a telephone circuit which can be detected by the average ear without special training.

Dbm

The number of dbm indicates the power of a signal, usually a single-frequency signal, in decibels with respect to an arbitrary reference level of one milliwatt. Thus, the fourth statement above could have been written, "The level at point B is −15 dbm," the minus sign indicating that the power is less than one milliwatt. One milliwatt is equal to O dbm.

The Neper

The neper is another logarithmic unit which is in common use in Europe and is often encountered in technical literature. It is abbreviated "nep".

The neper is based on the Naperian or natural system of logarithms. It is defined by the equation

$$N \text{ (in nep)} = -\log_{\varepsilon} \frac{E_2}{E_1} = -\log_{\varepsilon} \frac{I_2}{I_1}$$

with the implicit understanding that the circuit impedances are the same at the points where the two voltages or two currents are measured. The relation between the neper and the decibel is as follows:

$$N \text{ (in db)} = 8.686 \times N \text{ (in nep)}$$

$$N \text{ (in nep)} = 0.1151 \times N \text{ (in db)}$$

The Volume Unit

The general amplitude of an electrical speech or program wave is called its "volume" and is expressed in "volume units" or "vu". The volume in vu is numerically equal to the amplitude of the wave in decibels, related to an arbitrary "reference volume".

Speech and program waves vary greatly and irregularly from instant to instant. This makes it difficult to prescribe a simple method of measurement which will give uniform results when applied by different people. However, a standard technique was jointly adopted by major units of the communication industry in about 1940. The standard prescribes in detail the characteristics (speed of response, damping, scales, etc.) of a special measuring device known as a volume indicator. It also sets forth standard methods of calibrating this meter and the method for reading it. The unit vu can be correctly applied only to readings of speech or program volume, and to these only when the readings are made in the standard manner with an instrument having the standard characteristics. The volume indicator is so constructed and calibrated that it will read dbm directly on a steady sine wave. The mean power of a speech wave of reference volume (zero vu) is however different from one milliwatt.

DBRN and Dba

It is in terms of these units that electrical noise in telephone circuits is expressed when measured with the standard noise meters. A 1000 cycle sine wave whose power is one micro-microwatt (−90 dbm) will give a reading of 0 DBRN (db with respect to reference noise) or −5 dba (db adjusted). The noise meters are arranged to measure flat noise (equal response at all frequencies), or noise with message circuit or program weighting. When the weighting networks are used, the meter response is different at different frequencies. This makes it necessary to specify the type of weighting used in making a given measurement.

Obsolete Units

There are several units which are no longer in common use but which are occasionally encountered in the literature.

The Mile of Standard Cable was introduced as a unit of transmission loss at about the turn of the century. The American mile of standard cable was defined as the attenuation in one mile of the then standard 19 gauge telephone cable having a loop resistance of 88 ohms, a capacity of 0.054 microfarads, and negligible inductance and shunt conductance. (These "primary constants" of a line will be discussed in the next chapter.) In Europe, a similar unit was used in which the mile of standard cable had the same resistance and capacity but in addition had an inductance of one millihenry and a shunt conductance of one micromho.

In order to determine the transmission loss of any circuit, two observers would talk over the circuit and then over a variable length of standard cable. When the standard cable had been varied until the same volume of sound was obtained over it as over the circuit to be measured, the number of miles of standard cable was taken as the loss of the circuit. For example, if 18 miles of standard cable gave the same transmission as the tested circuit, that circuit was said to have a transmission equivalent of 18 miles of standard cable.

This unit became ambiguous when single frequency measurements were substituted for talking tests. The shunt capacity in the standard gave the mile of standard cable a loss which varied with frequency. To overcome this difficulty, an additional convention was adopted.

The 800 Cycle Mile, often called the "standard mile" or simply a "mile", was defined as the loss of a mile of standard cable at a frequency of 796 cycles. This convention established a definite unit of loss in which measuring apparatus could be calibrated and to which the loss of a circuit at any frequency could be referred.

The Transmission Unit, or TU, was introduced in 1923. It differed from the decibel discussed above in name only.

In 1928, the International Advisory Committee on Long Distance Telephony (an organization of representatives of European telephone administrations and The Bell System) recommended that two units for transmission measurement be universally adopted. One was the neper, which has been described above, the other was the "bel", named in honor of Alexander Graham Bell. The bel was defined as $-\log_{10}(P_2/P_1)$. This unit is extremely large compared to the values normally measured in practice. Hence, the practical unit is one tenth of a bel or the decibel. Since ten TU were equal to one bel, the TU became the db in use today.

TRANSMISSION RATING SYSTEMS

Thus far, we have been concerned with units for expressing relative energy levels. They give us means of describing the loss of a circuit, as well as comparing the power passing through a circuit under different conditions or through different circuits. These units are indispensable tools in transmission design and maintenance, but without additional techniques, they do not permit us to rate a telephone connection subjectively (or as a subscriber might rate it). Circuit loss alone is not a criterion of an overall connection's ability to transmit intelligence. Before we can tell anything about how well a connection will talk, we must have some method of evaluating and measuring the effectiveness with which telephones convert acoustical to electrical energy and vice versa. This is a fundamental requirement of any transmission rating system. Because the acoustical and electrical functions of a telephone are so closely tied in with the reactions of people, and because the units and methods of measurement are usually different in acoustics and electricity, the rating system problem is inherently complex.

There are many and varied possible ways of setting up a reference system, and four have been used in succession during the last fifty years. Each in turn has given way to a newer system which appeared superior in the light of experience and practice at the time. All four have had one principle in common. They established a procedure for comparing the circuit to be rated with a reference circuit whose electrical characteristics were definitely specified.

Transmission rating practices are again in a state of flux, so it appears desirable to consider not only the system which has been in use during the past twenty-five years, but a new system which has been proposed recently.

Working Reference System

In the early rating systems, overall connections were rated solely on the basis of the loudness of the voice heard over the receiving telephone by an observer. Transmission ratings made in this manner were called "volume transmission equivalents".

About twenty-five years ago, it appeared that a better measure of transmission performance would be based on the ability of the listener to receive, clearly and intelligibly, the sounds produced by the speaker's voice. These measurements should take account of such factors as distortion, noise, and sidetone, as well as loudness or volume. The introduction of improved instruments, which controlled sidetone and more faithfully reproduced the sounds of the speaker's voice, brought about the adoption of a new rating system in 1931. It is known as the Working Reference System.

The makeup of the Working Reference System is shown in Figure 4-1. The instruments are of the desk stand type, which were still common in plant when the system was adopted. The interconnecting equipment was selected to

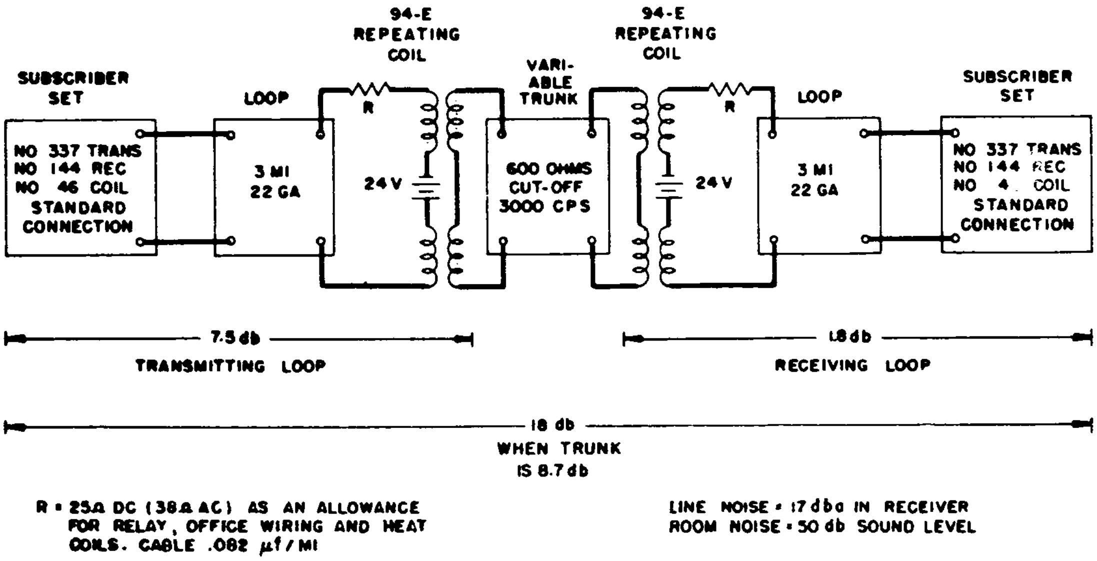


Figure 4-1. Working Reference System for the rating of Telephone Circuits.

simulate a typical connection of that time. A representative level of line noise is specified, as well as an average amount of room noise at the receiving instrument.

Figure 4-2 shows schematically how a circuit is rated in terms of the Working Reference System. In principle, a conversation is passed alternately over the reference system and the system being rated, while the loss of the reference system trunk is varied. When an equal number of repetitions per unit of time is required to pass information over the two systems, the loss of the reference trunk

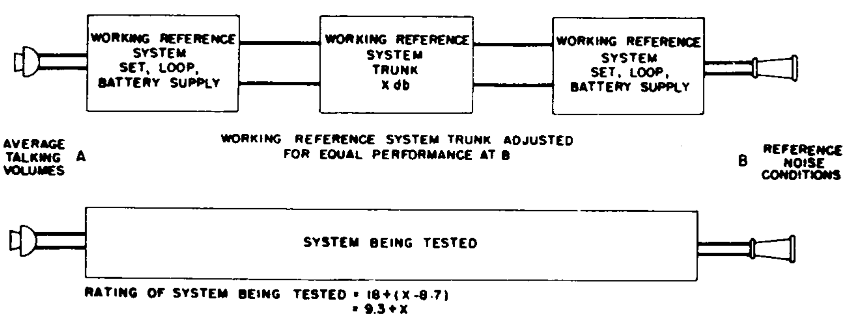


Figure 4-2. Rating an Over-all Telephone Connection.

(X db) is noted. The rating of the system under test is then (9.3 + X db). The larger the value of "X", the worse the circuit. (The constant 9.3 db is the sum of the transmitting and receiving loop losses of the Working Reference System, as determined on a "volume" basis, when compared with the earlier transmission rating system which it superseded.)

Let us consider an example. Suppose that we wish to rate a system consisting of two E1E hand sets, each connected to the same step-by-step office by 17,500 foot, 22 gauge, non-loaded loops. Comparative talking tests would show this system to require the same repitition rate as the Working Reference System with 1.7 db in the reference system trunk. The rating of this system would be (9.3 + 1.7) or an 11.0 "db effective" transmission equivalent. (The term "effective" is used to distinguish this type of rating from the volume transmission equivalents measured on the older rating systems and from single frequency power loss tests.)

The obvious question now is, "What does '11 db effective' mean?", but before we can answer this question, we must look into the history of this reference system a little more. — If the trunk setting in our example had been 8.7 db, the rating would be (9.3 + 8.7) or 18 db effective. (Remember 18 db! It is the magic number, and this is why.) At the time this rating system was worked out, an 18 db effective talk was considered representative of the service provided. Also, 8.7 db in the reference trunk established an over-all volume loss which facilitated correlation with the preceding volume rating systems. So 18 db effective over-all loss (9.3 in the loops plus 8.7 in the trunk of the Working Reference System) was selected as the benchmark or datum for all effective transmission equivalent ratings. — Now we are in a better position to interpret the rating we got in our example. What the "11 db effective equivalent" we obtained really means is that our connection will have an over-all intelligence transmitting ability that is (18 - 11) or 7 db better than the Working Reference System, when it has 8.7 db in the reference trunk.

Outside the Laboratories, this somewhat arbitrary datum of 18 db has generally lost its significance. This ambiguity has not been helped by the fact that our present day instruments are so superior to those used in the reference system that negative values of effective transmission loss have become common-place. Yet from a practical standpoint, saying that a telephone connection having a −4 db effective loss is a good circuit is no more irrational than saying it is hot when the thermometer reads 90° F. For in both cases the measurements are based on an arbitrary benchmark.

So we see that the effective db is very different from the units of transmission measurement which we talked about in the early part of this chapter. The "db" is simply a measure of the difference of two power levels. The "effective db" is the unit of reference trunk loss in the Working Reference System. It will be noted that the reference trunk has a uniform response in the important frequency range below 3000 cycles. Therefore, the unit is one of distortionless volume. In other words, an effective db produces the same change in repetition rate as a db change in distortionless volume.

Effective transmission losses have been determined in the manner described above for virtually all station-loop-office-trunk combinations. These data are the basis for the transmission design of today's exchange plant and are important considerations in much toll design.

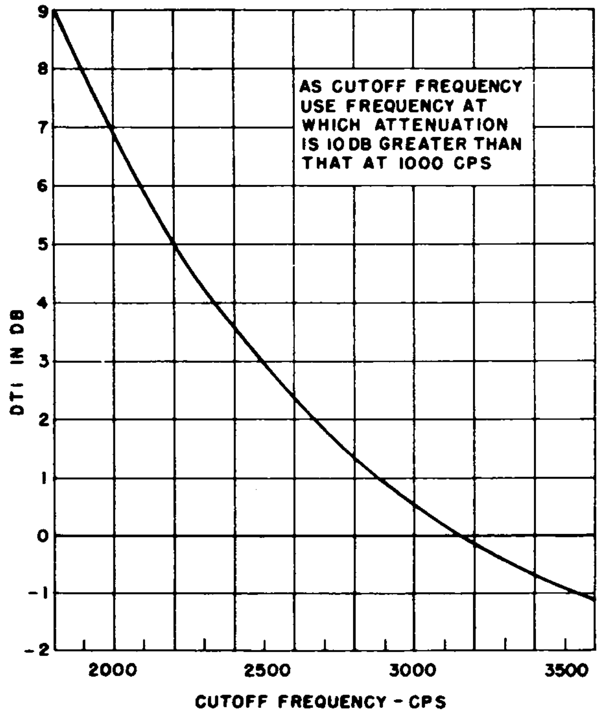


Figure 4-3. Distortion Transmission Impairments.

The Working Reference System has been used in another way. It has made it possible to determine the decrease in the loss of a connection necessary to offset the degrading effect (so-called Transmission Impairment) of such factors as noise, distortion, and sidetone. The result of one such study, that of Distortion Transmission Impairment (DTI), is shown in Figure 4-3. This curve indicates the change in circuit loss which will just overcome a change in the upper cutoff frequency of a facility. For example, a circuit which will pass only 2500 cycles must be 4 db shorter than one which will pass 3500 cycles, if both circuits are to have the same effective loss.

Loudness Rating System

The Working Reference System has served its purpose well, but in a sense, time has passed it by.

a. Improved response of modern station instruments and the general use of higher cutoff facilities have reduced the distortion impairment problem.

b. The plant is now virtually saturated with anti-sidetone sets.

c. Circuit noise has become less of a problem, with the advent of low contact noise switching equipment and better controls over power induction hum.

d. For most people, there is no tie between much of the effective transmission equivalent data and their own experience.

e. The comparison of circuits on the basis of repetition rate has become unnatural, simply because repetitions are seldom encountered today at least on local calls.

Recognizing these conditions, the Laboratories have developed a new rating system.

Since loudness has again become the main factor subject to variation in plant design, the new system for rating transmission performance is based on loudness measurements. The other transmission factors recognized by the effective loss system will not be discarded. Their effects will be expressed as penalties, which can be added to the loudness rating when a combined rating of all subjective effects is desired. This will give a form of effective loss, which will be referred to as "subjective" loss, to distinguish it from "loudness" loss and from the "effective" losses now in use. These transmission penalties will usually be small, and their use will be limited to special engineering applications and to the design of apparatus and systems.

The new loudness system differs radically from its predecessors, for circuits to be rated will not be compared with a standard equipment arrangement, such as the Working Reference System. Instead an over-all connection rating will be based on direct measurements of acoustic pressure at the transmitting and receiving telephone instruments.

If we call the sound pressure at the listener's ear S_L and the acoustic pressure at the talker's lips S_T, the rating of the over-all telephone connection, as defined by the new loudness system, will be

$$R_O \text{ (in db)} = -20 \log_{10} \frac{S_L}{S_T}$$

So here we are back to the decibel again. But this time, we have an equation that looks like the definition we saw earlier for a decibel in terms of a voltage ratio. This is as it should be, for in acoustics, sound pressure is analagous to voltage in an electrical circuit.

When the pressure of the sound waves entering and leaving the connection are the same, $S_L/S_T = 1$. Since the log of 1 is zero, the rating would be 0 db. When the output pressure from the receiver is less than the pressure at the talker's lips, we have a loss expressed in db. When it is greater, we have a negative loss or, in other words, an over-all gain.

When determining ratings, acoustic pressure will be measured in millibars. The millibar is a unit of pressure used in the physical sciences, such as meteorology. It is defined as 1000 dynes per square centimeter, which is about 0.0145 pounds per square inch (or about one thousandth of the normal atmospheric pressure).

You may wonder why acoustic pressure is to be used rather than acoustic power. There are two reasons. First, acoustic pressure is much easier to measure than acoustic power; second, the human ear seems to be a pressure-sensitive rather than a power-absorbing device, in the same way that a vacuum tube is voltage-operated rather than power-operated.

The equipment which has been developed for measuring acoustic pressures for the loudness rating system is shown in Figure 4-4. It has two parts, an artificial voice, and an artificial ear. The artificial voice has a source of wide band test power in the voice frequency range, a network to shape this voice frequency energy so that it simulates the frequency spectrum

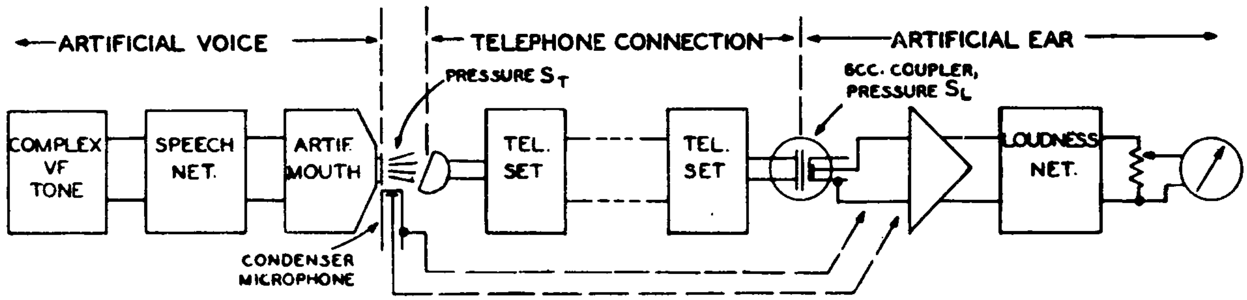


Figure 4-4. The Electro-Acoustic Transmission Measuring System.

of speech, and an artificial mouth to direct the sound energy into the transmitter of a telephone instrument. The artificial ear consists of a condenser microphone, an amplifier, a weighting network which approximates the response of the human ear, and an indicating meter. When pressure measurements are made at the input of a connection, the condenser microphone replaces the transmitter of the telephone set in front of the artificial mouth. Output measurements are made by placing the condenser microphone in a 6 cubic centimeter closed coupler pressed against the receiver of the receiving telephone instrument. The 6 cc coupler simulates the space volume of the average human ear when a receiver cap is placed against it.

The fact that pressure measurements are made with a meter will make it possible to obtain readings in the field as well as in the laboratory. This will permit the new system to be used in maintenance work as well as for design.

Thus far, we have only considered the ground rules and equipment for rating an over-all connection. The loudness rating system also makes provision for rating components of a connection. For instance, if S_T is the acoustic pressure (in millibars) at the transmitter of a telephone, and V_{TS} is the voltage (in volts) across a 900 ohm resistance load at the line terminals of the set, the "transmitting conversion loss" is defined as

$$C_T \text{ (in db)} = -20 \log_{10} \frac{V_{TS}}{S_T}$$

The voltage measurement is made with the artificial ear by replacing the condenser microphone with an input transformer. Using similar techniques, we can determine other component ratings and losses. Figure 4-5 shows how these components fit together to form the over-all rating. Since these components are all expressed in db, they may be added directly to determine any desired combination of losses.

There are several advantages to the new method of rating telephone transmission.

a. The rating is in terms of loudness, and this ties in with ordinary experience. Almost every one knows whether one sound is louder than another and has a general idea of how great the difference is.

b. The over-all rating of a connection will be its actual loss or gain. The loss will be a positive number if less comes out than was put in, and will be negative if more comes out than was put in. For instance, a loudness rating of 6 db would mean that the sound delivered to the listener's ear by the receiving set is only half as loud as the sound delivered to the transmitter by the speaker.

c. It will be possible to use the same numbers for engineering and maintenance. Simple testing equipment can be provided to measure the performance of telephone sets in the field. This will be an aid to trouble location.

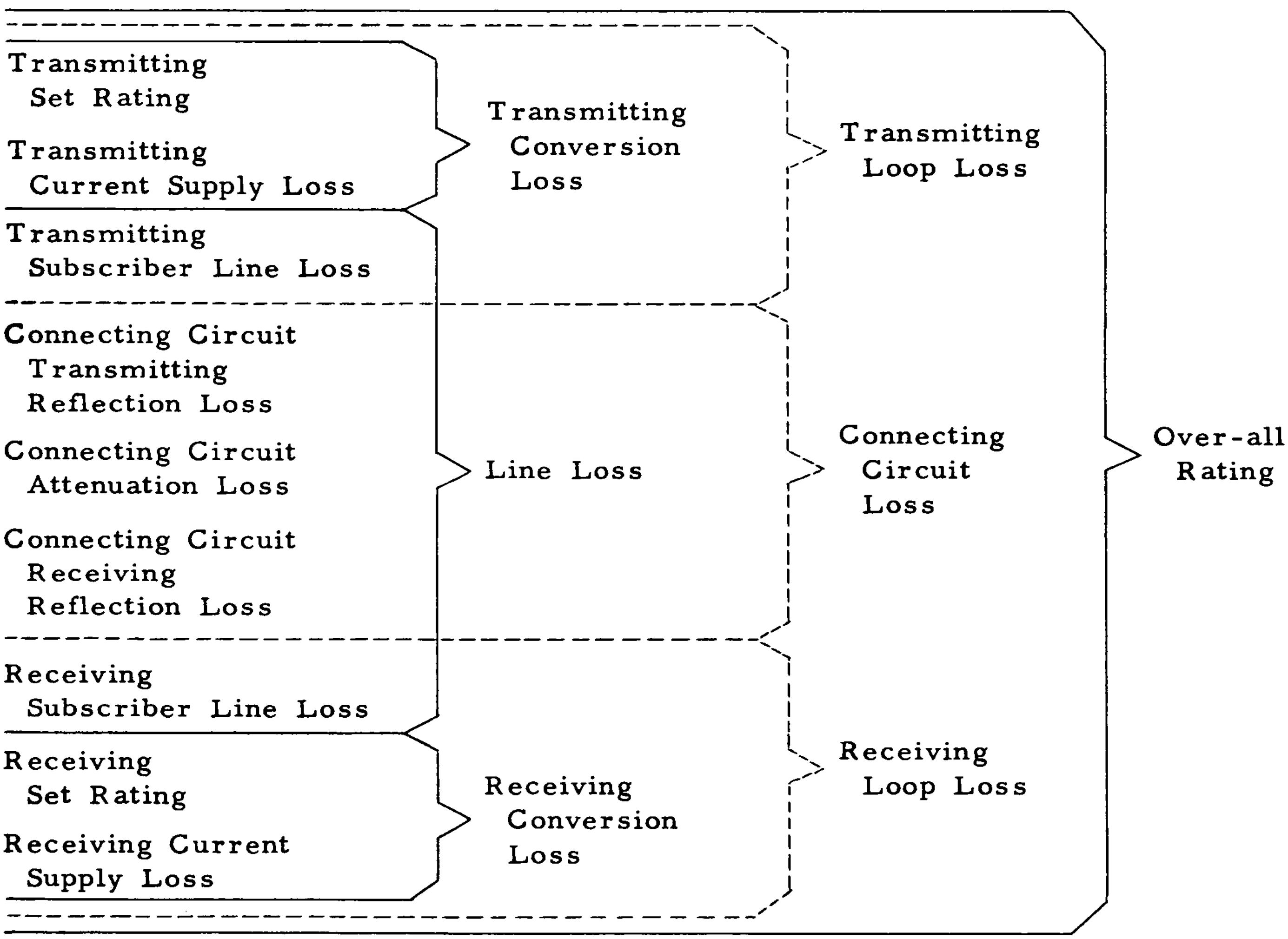


Figure 4-5. Components For Rating an Over-all Interoffice Telephone Connection.

CHAPTER 5

TRANSMISSION LINES

Preceding discussions have dealt with networks made up of resistors, capacitors, and inductors. Implicitly, these were units such as those found in familiar electrical equipment. Such units are called lumped constants. A transmission line is an electrical circuit whose constants are not lumped but are evenly distributed over its length. The theory of lumped constant networks can be applied to transmission lines, but lines exhibit additional characteristics which deserve consideration.

Equivalent Circuit

Fundamentally, a transmission line is a pair of conductors uniformly spaced and extending for a considerable distance. These conductors have resistance. And since the two conductors form a one turn coil, they have inductance. If we wish to construct a lumped constant network that is electrically equivalent to a line, we must start with a resistor (R) and an inductor (L) connected in series. But there are other factors to consider. The insulation between the line wires is never perfect; there is some leakage between them. The leakage resistance may be very large, as in a cable, or it may be fairly small in the case of a wet open wire lead. In any event, our equivalent circuit must contain a resistor (G) in shunt between the line conductors. Any two conductors separated by an insulator have the properties of a capacitor. So our circuit must have a capacitor (C) in shunt. Finally, a line appears the same electrically when viewed from either end, and our equivalent circuit must also be symmetrical. In the discussion of networks, it was suggested that any circuit could be simulated with a T-structure. It is not surprising then to find that our equivalent circuit for a transmission line is the T-network shown in Figure 5-1. R, L, C, and G are called the "primary constants" of a transmission line. For convenience, we can

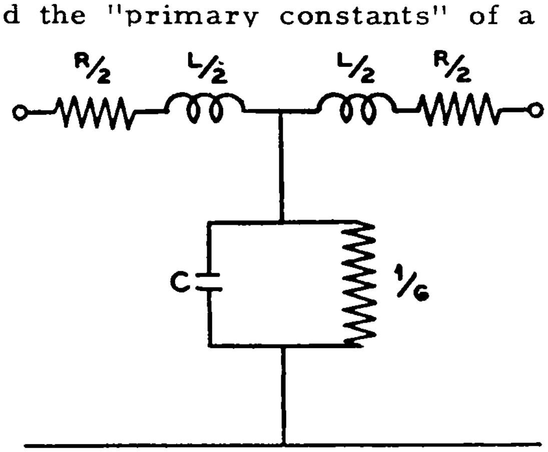


Figure 5-1. Primary Constants of a Section of Uniform Line.

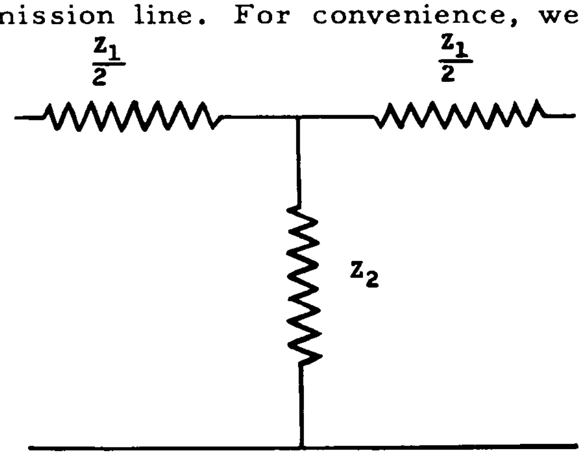


Figure 5-2. Equivalent Network of a Section of Uniform Line.

lump the series constants R and L into an impedance Z_1 and the shunt constants C and G into another impedance Z_2 as has been done in Figure 5-2.

The equivalent circuit in Figure 5-1 or 5-2 is a poor approximation of a real line, for we have lumped all of the distributed constants at one point. All of the leakage, for instance, does not occur at the center of the line. We could improve the approximation by having two T-sections in series, each containing half of the line constants. The best approximation would be to have an infinite number of T-sections, each having the constants of an infinitely short section of the real line.

Characteristic Impedance

Let us simulate an infinitely long line with an infinite number of identical recurrent T-networks as suggested by Figure 5-3.

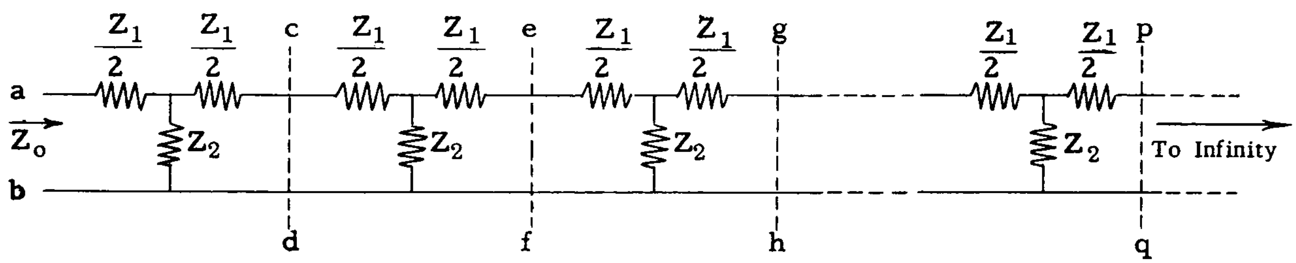


Figure 5-3. Uniform Line Simulated by a Large Number of Identical Networks.

If we measure the impedance looking into the terminals a-b, we shall obtain a value Z_0. Suppose now that we open the line at c-d and again measure the impedance of the line looking to the right. The effect of removing one section from an infinite number of sections is negligible, so we would still measure Z_0.

The impedance at a-b was Z_0 when the first section was connected to an infinite line presenting an impedance Z_0 at c-d. If we terminate the first section at c-d with a lumped impedance having a value Z_0, we shall still measure Z_0 at a-b.

This impedance Z_0 is called the "characteristic impedance" of the line. As might be expected it is determined by the values of the primary constants of the line. It is related to the equivalent T-structure in Figure 5-2 by the expression:

$$Z_0 = \sqrt{\frac{Z_1^2}{4} + Z_1 \times Z_2}.$$

The impedances Z_1 and Z_2 contain inductance and capacitance. Since the reactance of an inductor and capacitor change with frequency, the characteristic impedance of a transmission line also changes with frequency. This property must be recognized when selecting a network which is to terminate a line in its characteristic impedance over a band of frequenices.

It is often more convenient to determine Z_o by test. This can be done by measuring the impedance presented by the line when the far-end is open-circuited (Z_{oc}) and when it is short-circuited (Z_{sc}). Then

$$Z_o = \sqrt{Z_{oc} \times Z_{sc}}.$$

To summarize, every transmission line has a characteristic impedance, Z_o. It is determined by the materials and physical arrangement used in constructing the line. For any given type of line, Z_o is a constant regardless of the line's length, but it will vary with the frequency of the signal transmitted.

The term characteristic impedance should be applied only to uniform transmission lines. The corresponding property of a lumped constant network is called "image impedance". Figure 5-4 represents the equivalent T-structure

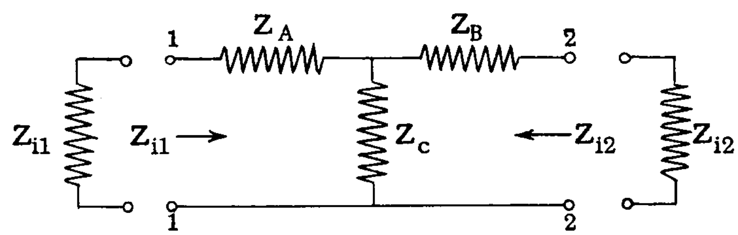


Figure 5-4. Image Termination of a Non-Symmetrical Network.

of any lumped constant network. If we measure the impedance presented at terminals 1-1, when terminals 2-2 are open-circuited and short-circuited, we can compute an impedance $Z_{i1} = \sqrt{Z_{2oc} \times Z_{2sc}}$. Repeating the process from the right-hand side of the T will give us $Z_{i2} = \sqrt{Z_{1oc} \times Z_{1sc}}$. The impedances, Z_{i1} and Z_{i2}, are the image impedances of the network.

If we terminate the network in its image impedances (that is, connect Z_{i1} to 1-1 and Z_{i2} to 2-2), we have created a unique condition. For the impedance looking in either direction from 1-1 will be Z_{i1}. Similarly, the impedance either side of 2-2 will be Z_{i2}.

If the network is symmetrical (that is, $Z_A = Z_B$), it will have a single image impedance $Z_i = Z_{i1} = Z_{i2}$. Under these conditions, network image impedance is analogous to the characteristic impedance of an uniform line.

We will find application of the characteristic and image impedance concepts when we consider the problem of reflections in transmission systems.

Propagation Constant

We have seen that a line of infinite length (or of finite length when terminated in Z_0) has a special property; at every point along the line, the impedance is the characteristic impedance, Z_o. Now impedance is just another way of saying voltage divided by current (E/I). So for Figure 5-3, we can write the equation:

$$\frac{E_{ab}}{I_a} = \frac{E_{cd}}{I_c} = \frac{E_{ef}}{I_e} = \frac{E_{gh}}{I_g} = Z_o.$$

Bear in mind that the voltage and current are not constant as we proceed down the line — their ratio is constant. The voltage and current actually decrease. This follows from Kirchoff's Laws. The voltage E_{cd} is less than E_{ab} by the voltage drop across Z_1, and the current I_c is less than I_a by the current shunted back through Z_2. These effects result in only a portion of the signal entering the line at a-b being passed on to the next section of line at c-d. Suppose that the energy reaching c-d is 1/2 of that supplied at a-b. Since the line constants are uniformly distributed, the energy reaching e-f will be 1/2 of that at c-d. So the signal at e-f will be 1/2 of 1/2, or 1/4, of the original signal we sent at a-b. This decrease in energy, as a signal is propagated down a line, is called "attenuation".

We need some method of expressing the way a line will modify the signal we wish to transmit. The equation above, and a little algebra, will show that

$$\frac{I_a}{I_c} = \frac{I_c}{I_e} = \frac{I_e}{I_g} = \text{some number.}$$

This number is called the "propagation constant". It is the ratio of the currents flowing at equally spaced points along a uniform line.

The mathematics get a little involved, but it works out that the propagation constant is actually two numbers in one: an "attenuation constant" and a "phase constant".

a. The "attenuation constant" tells what fraction of the current entering a section of line is passed on to the next section. In other words, it is a measure of the rate of decay of the current transmitted. Since the impedance is the same at all points along a uniform line, the attenuation constant is also a measure of the difference in power at the two ends of each section of line. Attenuation is calculated in nepers per mile, but for practical application the result is usually converted to "db per mile".

b. The "phase constant" is a measure of the time required for the current to pass through a section of line. It is calculated in "radians per mile". For our purposes, we can consider the phase constant in the more familiar form of "velocity". Velocity can be expressed in "miles per second". Theoretically the maximum possible velocity of propagation would be the speed of light or radio waves in free space, which is 186,000 miles per second.

These constants have been determined for the common types of transmission lines at typical operating frequencies. They are tabulated in the AB40 Sections of the Practices, and a few typical values are shown in Tabel 5-1.

TABLE 5-1

Attenuation and Velocity of Typical Facilities

	Attenuation db per mi.	Velocity mi. per sec.
104 mil Copper Open Wire		
1000 cycles	0.067	176,000
140 kc	0.308	183,000
19 gauge Toll Cable		
1000 cycles	1.06	47,200
60 kc	3.78	124,000
150 kc	6.02	129,000
19 gauge H88 loaded Cable		
1000 cycles	0.36	14,300

You will note in Table 5-1 that attenuation and velocity are different for each type of facility. This is reasonable when we consider that the propagation constant is determined by the R, L, C, and G of a line. Attenuation and velocity also vary with frequency, since the opposition to current flow offered by L and C depends on the frequency of the signal. In general the higher the frequency, the greater the attenuation and the greater the velocity.

The variation of attenuation and velocity with frequency results in two types of distortion:

a. Frequency distortion - Signals of different frequencies suffer different amounts of attenuation in traversing the line. Hence, they will be received at different relative levels.

b. Delay (or phase) distortion - Having different velocities, signals of different frequencies which are transmitted simulataneously will not be received at the same time.

Although the attenuation constants expressed in db (as in Table 5-1) are not impressive numerically, they can add up to tremendous losses in transmission over practical distances. Remember that each section of line (say one mile) reduces the signal transmitted by an equal proportion — not an equal amount. One of the great challenges in the development of telephony has been getting a usable amount of signal to the far end of a transmission line. The strong arm approach is to put a large enough signal into the sending end of the line, but very often this is not a realistic solution.

Consider a 19 gauge cable with a loss of about 1 db per mile. Thirty miles would have a loss of 30 db. Expresses as a power ratio this would be 1/1000. To receive one microwatt, we would have to send 1000 microwatts or 1 milliwatt. This is not unreasonable.

Now suppose that the line is a hundred miles long. The attenuation is 100 db, and we must send ten billion times the power we wish to receive. Ten billion dollars has become a rather commonplace figure, but 10,000,000,000 microwatts is 10,000 watts. That's enough power to run an electric stove, and don't forget stoves are usually hooked up to 220 volts with #6 or #8 wire. Obviously, this is not the way to run a telephone system.

The glaring error in this example is that we have chosen the wrong facility for our 100 mile line. Table 5-1 shows that the attenuation of 104 copper open wire is 0.067 db per mile. Had we used this type of construction, the line would have a loss of 6.7 db. This would be a power ratio of 1/4.7, or we would have had to send only 4.7 microwatts to receive one microwatt.

Electrically, the open wire and cable pair in our example differ only in the values of their primary constants. These values are compared in Table 5-2.

TABLE 5-2

Line constants of 19 ga. Toll Cable
and 104 mil Copper Open Wire at 1000 Cycles

		per loop mile	19 ga. Ca.	104 cu. O.W.	Ratio Ca./O.W.
Attenuation		db	1.06	0.067	15.8
Resistance	R	ohms	84.	10.	8.4
Inductance	L	millihenrys	1.12	3.66	0.3
Capacitance	C	microfarads	0.062	0.0085	7.3
Leakage	G	megohms	1.	19.	0.05

The data for only two types of lines are not sufficient for us to establish any definite mathematical relations between line constants and attenuation, but the right-hand column of the table tells a story. We can draw a few general conclusions by comparing this information with the equivalent circuit of a line in Figure 5-1.

When current passes through a resistance, a portion of the electrical energy is converted into heat. This heat is dissipated, and the energy is lost to the electrical circuit. In the table, the higher resistance cable has a greater attenuation than the lower resistance open wire. This relation between series resistance and loss is universal among electrical circuits. Whether they are transmission lines, communication networks, or power systems, less series resistance means less loss.

The relation between line inductance and attenuation is a little tricky. It is part of the story of loading, and we will consider that subject by itself.

Line capacitance provides a shunt path between the conductors for alternating currents. All current taking this path returns to the sending end of the line; it is not passed on to the next section. Therefore, capacitance contributes to attenuation. In Table 5-2, we note that the 0.062 mfd/mi cable has more attenuation than the 0.0085 mfd/mi open wire. A capacitor passes current more easily as frequency is increased, and line capacitance is primarily responsible for attenuation increasing with frequency.

Leakage also constitutes a shunt on the line, but the leakage comparison in Table 5-2 is a little deceptive. Under normal conditions, our construction techniques hold leakage resistance to such high values that it has little effect on line loss. However, the reduction of leakage resistance can materially increase attenuation. "Wet cable" and "trouble" are synonymous. Rain increases the attenuation of open wire, but not to the same degree that water effects the loss of cable.

To summarize, if a line is to have low attenuation, it must have:

a. Low series resistance,

b. Low capacitance, and

c. High shunt leakage resistance.

Loaded Lines

Table 5-2 shows that the high attenuation cable has only 30% of the inductance per mile of the low attenuation open wire. This leads to a question which we have avoided earlier. "Does more inductance in the line mean less attenuation?" The answer is, "yes and no". High inductance in a line does not necessarily mean low attenuation. But in this case more inductance would decrease the loss in either the cable or open wire considered.

Adding inductance to line conductors artificially is known as **"loading"**, and the circuit becomes a "loaded line".

The reasons why increasing L should reduce attenuation are not immediately apparent. A precise explanation of loading is extremely involved, but we can get a clue to the explanation if we start by reviewing the effect of R.

Electrical power loss is expressed by the familiar equation,

$$\text{Power loss} = I^2 \times R.$$

We have already considered reducing attenuation by reducing R. But we see that we could also reduce I^2R loss in the line by reducing the line current, I. In fact, this would pay real dividends for power dissipated by the line would decrease as the square of the current. So the problem becomes how to reduce I.

The next step is to recall another law of electricity,

$$\text{Electrical energy} = E \times I.$$

This suggests that we can reduce line current, without changing the energy in the signal transmitted, if we could increase line voltage at the same time. For example,

$$2 \text{ volts} \times 2 \text{ amps} = 4 \text{ watts, also}$$

$$4 \text{ volts} \times 1 \text{ amp} = 4 \text{ watts.}$$

We have the same amount of energy under both conditions, but in the second case we have been able to cut the current in half by doubling the voltage.

We found that characteristic impedance is the ratio of line voltage to line current, or

$$Z_o = \frac{E}{I}$$

If at a point in a line, we measure 2 volts and 2 amps, the characteristic impedance of the line must be

$$\frac{2 \text{ volts}}{2 \text{ amps}} = 1 \text{ ohm} = Z_o$$

If in another line, we measure 4 volts and 1 amp, this second line must have an impedance

$$\frac{4 \text{ volts}}{1 \text{ amp}} = 4 \text{ ohms} = Z_o$$

Now the relation between Z_0 and E/I is a two-way street. By changing Z_0, we can force a change in the ratio of voltage to current. This technique will accomplish the desired results. The 4 ohm and the 1 ohm line will both carry 4 watts, but the 4 ohm line will do the job with less current. And this means less I^2R loss.

The next question is, "How can we increase line impedance?". If it is not immediately apparent that an increase in L will increase Z_0, we can recall an equation offered earlier in this Chapter,

$$Z_0 = \sqrt{\frac{Z_1^2}{4} + Z_1 \times Z_2},$$

where Z_1 is the impedance of the series elements and Z_2 is the impedance of the shunt elements of the equivalent T-structure of a uniform line. The series inductive reactance is a part of Z_1, so an increase in L must result in an increase in Z_0.

To recapitulate the argument: increasing L increases Z_0; with higher line impedance, the same energy can be transmitted with less current; less line current means less I^2R loss; reducing the power dissipated by the line must reduce its attenuation. Some liberties have been taken in this argument; perhaps the least is the unrealistic values selected for illustration. Another is the disregard of phase angle. (Phase angle is implicit in any impedance and alternating voltage or current, but phase has been purposely avoided throughout these discussions because it seems to bother some people.)

The line of thinking we have followed is correct as far as it goes. The trouble is that it doesn't go far enough. For we might proceed to the erroneous conclusion that a line having infinite inductance would have minimum loss. Actually, a complete analysis would show that the ideal relation between line constants is L = GRC.* This condition would give distortionless transmission. Attenuation would be low, and both attenuation and velocity would be independent of frequency. In other words, such a line would cause neither frequency nor delay distortion. Unfortunately, it is impossible to construct a transmission line with this ideal relation between the line constants.

In practice, the ideal can be approached by adding series inductance to a line. This has been done in two ways. The more effective (and by far the more expensive) method is to wrap a layer of magnetic material over the line conductor. Such a line is said to be "continuously loaded".

The more practical approach is to insert a coil in each wire at regular intervals. A line treated in this manner is said to be "lumped loaded". The improvement made in attenuation by a typical lumped loading scheme is shown

*Throughout these discussions, leakage (G) is considered as resistance, measured in megohms or millions of ohms. In the literature, leakage is frequently expressed as the reciprocal of resistance (ie. conductance), measured in micromhos or millionths of a mho. Resistance is used here since it is the more common term.

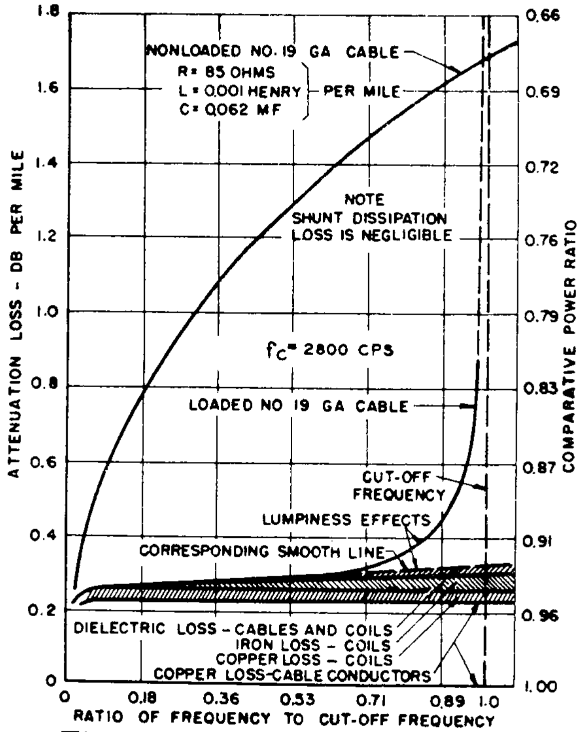


Figure 5-5. Effect of Loading on Attenuation.

in Figure 5-5. The curve for the loaded line shows that attenuation is materially decreased, but only over a limited band of frequencies. This typical attenuation characteristic for a lumped loaded line is explained by Figure 5-6. For the equivalent circuit for a lumped loaded line is a low-pass filter. (The leakage resistance has been omitted from this equivalent circuit because it is comparatively unimportant in determining the transmission characteristics of a practical loaded line.)

Loading has three effects on the transmission characteristics of a line within the pass-band: it decreases attenuation, it decreases velocity, and it increases the characteristic impedance.

Two considerations govern the design of a lumped loading scheme: The wider the desired pass-band, the smaller the loading coil inductance; the higher the frequency to be transmitted, the shorter the line section between loading coils.

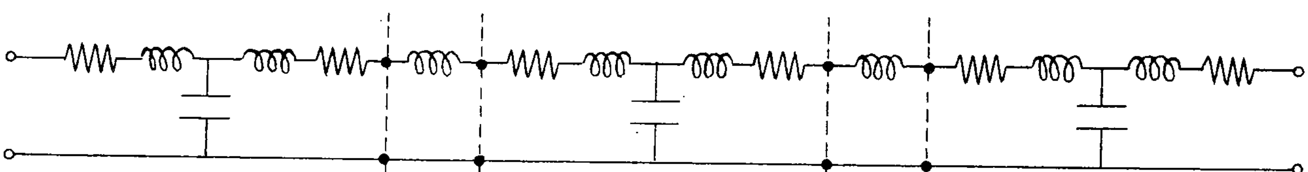


Figure 5-6. Equivalent Circuit of Lumped Loaded Line.

A loading coil introduces an impedance discontinuity into an otherwise smooth or uniform line. This effect is offset by making the spacing between loading coils short, compared to the wave length of the signal to be transmitted, and by spacing the coils with precise regularity. However, the introduction of lumped constants destroys the characteristic impedance of the structure. Actually, a lumped loaded line develops two characteristic impedances: one at "mid-coil" (that is at the electrical center of each loading coil); the other at "mid-section" (that is at the middle of each line section, half way between load points). The mid-coil and mid-section impedances will have different values. At other points along each section, the line will be found to have intermediate values of impedance. These impedances will be different looking in the two directions.

Lumped loading has been used on both aerial wire and cable in the Bell

System. However, open wire loading was abandoned about thirty-five years ago when carrier operation was introduced. Today, lumped loading is in general use on voice frequency cables, both toll and exchange. Toll entrance and intermediate cables are frequently loaded to give the cable the same impedance as the connected open wire. Lines for cable carrier systems are usually non-loaded.

Each load point inductance is equally divided between two coils; one coil is cut in series with the tip conductor, the other is cut in series with the ring. The two coils are wound aiding on a single core. Phantom loading units have four coils on one core; the two windings to be cut into one side of a quad are poled bucking for side circuit metallic currents. Hence, the phantom unit places no net inductance in the side circuits.

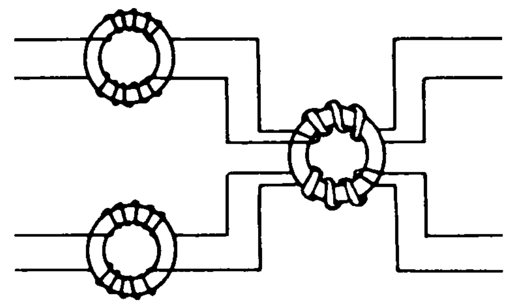


Figure 5-7. Typical Arrangement of Loading Coils.

A number of loading arrangements have been standardized in the Bell System. The spacing between coils, or "loading section" length, is designated by a series of code letters. The codes for the more common spacings are:

B	3,000 feet	H	6,000 feet
C	929 feet	M	9,000 feet
D	4,500 feet	X	680 feet
E	5,575 feet	Y	2,130 feet

The spacing code is followed by a number indicating the inductance of the loading coils in millihenrys. If the facility is a loaded quad, this number indicates the side circuit loading. It is followed by a second number showing the inductance inserted in the phantom circuit. In certain toll entrance loading arrangements, the side and phantom circuits are loaded at different intervals. Then two spacing codes are used; the first code indicates the side circuit coil spacing, the second indicates the phantom coil spacing.

The following abbreviations are typical:

H-88	88 mH every 6,000 feet
H-44	44 mH every 6,000 feet
B-22	22 mH every 3,000 feet
H-88-50	88 mH every 6,000 feet on each side circuit 50 mH every 6,000 feet in the phantom
CE-4.8-12.8	4.8 mH every 929 feet on each side circuit 12.8 mH every 5,575 feet in the phantom (Phantom Circuit loading units are applied at every sixth side circuit load point.)

Reflection

We have considered only lines which are uniform and which are terminated in their characteristic impedance. As long as the signal is presented with the same impedance at all points in a connection, the only loss is attenuation.

If we join one circuit with an impedance Z_{oA} to a second circuit with an impedance Z_{oB}, we cause an additional transmission loss. While the signal is traveling in the first circuit, it has a voltage-to-current ratio $E_A/I_A = Z_{oA}$ But before the signal can enter the second circuit, it must adjust to a new voltage-to-current ratio $E_B/I_B = Z_{oB}$. In making this adjustment, a portion of the signal is reflected back towards the sending end of the connection.

It is not surprising that there should be a reflection at an abrupt change in the electrical characteristics of a line. There is a disturbance in any form of wave energy at a discontinuity in the transmission media. Sound is reflected from a cliff. Light is reflected by a mirror. These conditions are equivalent to a line terminated in an open- or short-circuit — all of the energy in the incident wave is reflected. A less abrupt change in impedance will cause a partial reflection. When we look into a pool of water, we see the landscape mirrored in the surface — part of the light falling on the water is reflected. We also see the bottom of the pool, if it is not too deep — part of the light falling on the water passes through the discontinuity of the air-water junction and illuminates the bottom. Such a partial reflection occurs when two circuits with different impedances are joined, as in Figure 5-8. The power (P) in the signal arriving

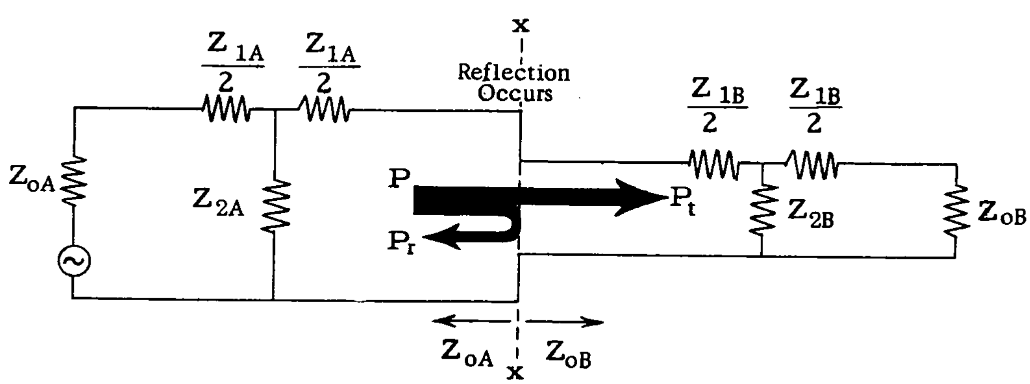


Figure 5-8. Reflection at Impedance Discontinuity.

at the junction x-x is divided. A portion of the signal (P_t) is transmitted through the junction. The remainder of the signal (P_r) is reflected and travels back towards the source.

Several ways have been developed for recognizing the effect of an impedance discontinuity on transmission. The one most generally used is reflection loss.

"Reflection loss" is the difference in db between the power transferred between two circuits and the power that would be transferred if the two circuits had identical impedances. At the junction x-x in Figure 5-8,

$$\text{Reflection loss (in db)} = 20 \log_{10} \frac{2\sqrt{Z_{oA} \times Z_{oB}}}{Z_{oA} + Z_{oB}}$$

The over-all loss of two circuits having different impedances is the sum of the attenuation of the two circuits and the reflection loss at their junction.

It is possible to have negative reflection loss, or reflection gain. This does not mean that power can be generated at an impedance discontinuity. It results from the choice of identical impedances as the reference condition for zero reflection loss. This is not the condition for maximum power transfer. As pointed out in Chapter 2, the power transferred from one network to another will be a maximum when the impedances on each side of the junction are conjugate. That is, when the two impedances have equal resistive components and their reactive components are equal and opposite.

When there is more than one discontinuity in a transmission system, a portion of the signal reflected at one junction will be re-reflected at the others. This is taken into account by adding "interaction loss" to the reflection losses and attenuations.

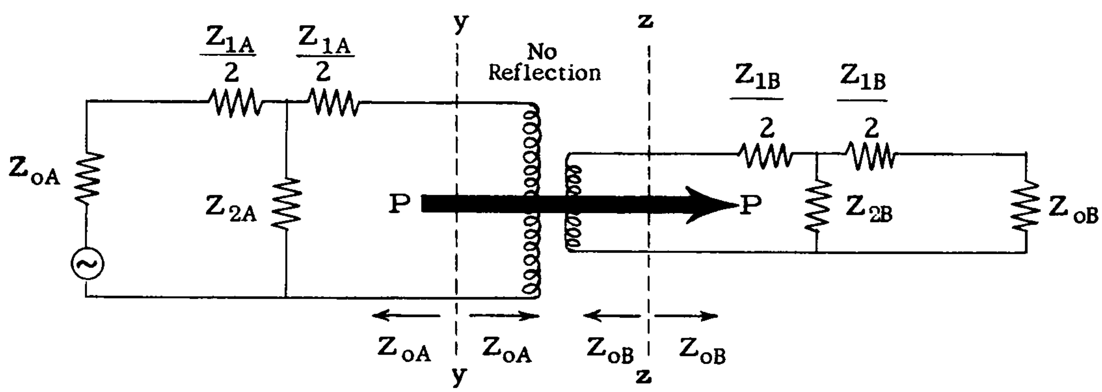


Figure 5-9. Unequal Impedances Matched with a Transformer.

An impedance discontinuity can be eliminated by introducing an impedance matching device at the junction.

a. In Figure 5-9, the line to the left of y-y (Z_{oA}) does not match the line to the right of z-z (Z_{oB}). By cutting a transformer of turns ratio $Ny\text{-}y/Nz\text{-}z = \sqrt{Z_{oA}/Z_{oB}}$ into the circuit between y-y and z-z, the line to the left of y-y is made to look into an impedance Z_{oA}, while the line to the right of z-z looks back into Z_{oB}. In practice, such a transformer will have a loss of a fraction of a db, but the reflection loss will be made essentially zero. Typical examples of this technique are: the induction coil in a station set, an inequality ratio coil in a trunk equipment, and the input and output transformers in a repeater amplifier.

b. A network (or pad) with image impedances of Z_{oA} and Z_{oB} would give the same result as the transformer in Figure 5-9. Impedance matching pads find limited application; because, they have a minimum loss determined by their image impedance ratio. For example, a pad with image impedances of 600 and 500 ohms (a ratio of 1.2) would have a loss of at least 3.75 db; one with a ratio of 2 would have a minimum loss of about 8 db.

c. At very high frequencies, it is practical to match impedances by introducing a section of transmission line with gradually changing dimensions. The most common application of this technique is the tapered open wire line between a TV antenna and the twin-lead running to the receiver.

d. We have noted that the impedance of a lumped loaded lines varies gradually between mid-section and mid-coil. This permits us to match impedances by terminating a loaded line at the proper point. Compensated loading, or impedance compensation, (which will be discussed in Chapter 7) is an extension of this technique.

In some cases, we are more interested in the amount of power reflected at a junction than in the loss to the signal transmitted through the discontinuity. This question arises principally in studies of echo and in the design of 2-wire repeatered circuits.

"Return loss" is the loss in db between the power in a signal arriving at an impedance discontinuity and the reflected signal. If the two impedances at a junction are matched, the return loss will be infinite, since there will be no energy reflected. The greater the difference between impedances on each side of a junction, the less the return loss. At the junction x-x in Figure 5-8,

$$\text{Return loss (in db)} = 20 \log_{10} \frac{Z_{oA} + Z_{oB}}{Z_{oA} - Z_{oB}}$$

In today's plant, the most serious source of low return loss is 4-wire terminating sets whose balancing network does not match the impedance of the office wiring. This situation is sometimes described as low or poor office balance.

CHAPTER 6

TRANSMISSION SYSTEMS

The first telephone transmission system consisted of the instruments and the pair of wires in a Boston attic which carried Dr. Bell's summons for Thomas Watson. Metallic pairs are still the most commonly used transmission link between telephone sets, but the past eighty years have seen a number of additions to the telephone engineer's bag of tricks. This chapter very briefly describes the more common instrumentalities in use today and indicates their fields of application.

Before taking up specific systems, it may be well to clarify a few general terms.

"Voice Frequency Systems" are those which transmit intelligence over the line at frequencies which fall within the useful portion of the audible spectrum, in general that lying between about 200 and 4000 cycles per second.

"Carrier Systems" are those which employ some form of modulation at each end of the circuit, so that the signal is transmitted at frequencies above the principal audible range.

"Two-Wire Operation" - By its basic nature a telephone conversation requires transmissions in both directions between the customers at opposite ends of a transmission system. In the early days of telephony, most transmissions were made over paired conductors (or wires) and the transmissions in opposite directions used the same electrical path between the customers. At switching points the two transmission path terminals of one circuit were connected through cord circuits or switching mechanisms to the two transmission path terminals of a similar circuit. This method of transmission and switching was therefore designated as two-wire operation.

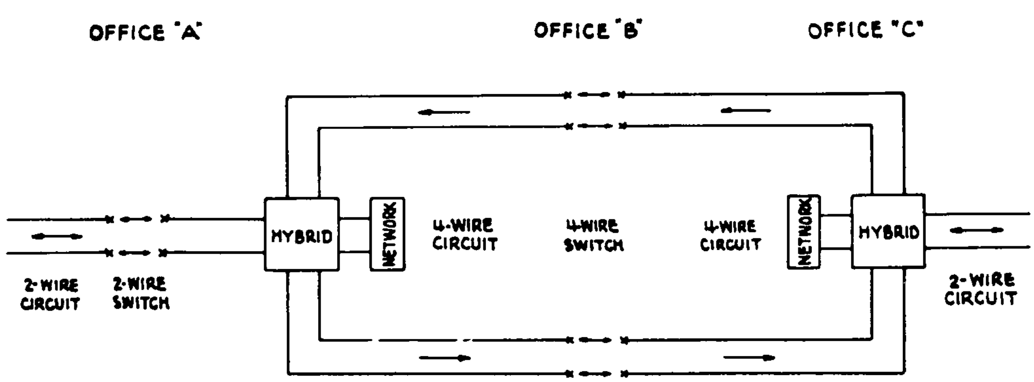


Figure 6-1. Two-Wire and Four-Wire Operations.

Thus by definition, transmission and switching operations are "two-wire" when oppositely directed portions of a single conversation occur over the same electrical transmission path or channel.

"Four-Wire Operation" - When carrier system operation was introduced into the open wire plant and circuits of increasingly greater length were routed in cable plant, echo and singing considerations made it necessary to separate the electrical paths used for oppositely directed transmissions between the customers involved in a single conversation. This separation is accomplished by either or both of two methods, as follows:

a. Separate pairs in outside plant and office cabling

b. Separate carrier frequency bands

In the larger intertoll switching mechanisms used today such separation is also maintained through the switches.

Because two separate pairs (or 4 wires) were used for the oppositely directed transmission paths of many of the longer voice-frequency circuits in cable, circuits operated in this manner were designated as "Four-Wire" circuits.

Thus, by definition, transmission and switching operations are "Four-Wire" when the oppositely directed portions of a single conversation are routed over separate electrical transmission paths or channels.

A distinction is sometimes made between the two methods of four-wire operation. Systems using the same frequency band in two separate paths for the two directions are said to give "real four-wire operation"; those using two frequency bands over a single path are said to provide "equivalent four-wire operation".

"Frogging" - In railroad operations it is sometimes necessary for rails to cross each other. The device used at such cross-over points is known as a "Frog" in railroad vernacular.

In telephone operations, it is sometimes necessary to cross over from one electrical transmission path to another at some point other than at a switching center. Such cross-overs are made to equalize transmission losses or to reduce cross-talk between circuits. This is done by:

a. Interchanging circuits between two parallel cables at an intermediate repeater station. See K-Lines in Figure 6-12.

b. Interchanging high and low frequency carrier system allocations at an intermediate repeater station. See Figure 6-17.

By definition the interchange, or cross-over, from one transmission path or channel to another at some point other than at a switching point has been designated as "Frogging".

TELEPHONE INSTRUMENTS

The telephone instrument is the connecting link between the subscriber and the electrical transmission circuit. It must convert sound energy into electrical energy and the reverse. The degree of efficiency and fidelity with which it performs these functions has a vital effect upon the quality of transmission of the service we provide.

Transmitters - The conversion of acoustic energy to electrical energy may be accomplished in various ways, but for telephone purposes, the carbon granule transmitter is almost universally used. It consists essentially of a chamber containing finely divided carbon, closed by a movable electrode connected to a diaphragm. Current from a battery flows from one electrode to the other through the carbon grains. When a sound wave impinges on the diaphragm, the variations in air pressure are transferred to the carbon, and as a result, the resistance of the path through the carbon changes in proportion to the pressure. Hence when the transmitter is agitated by a sound wave, the direct current which flows in the quiescent state is changed to a pulsating current. A current of this nature may be considered as being made up of a direct current component plus an alternating current component. In the ideal case, the a-c component of the transmitter current reproduces exactly the wave form of the original signal and furnishes the medium for conveying intelligence to the distant end of the circuit.

Practical transmitters of course depart from the ideal and, as a consequence, the wave form of the electrical output is not identical with that of the impressed sound wave. Among the sources of distortion in transmitters are:

a. Mechanical resonance of the moving parts, which results in increased output at the resonant frequencies.

b. Differences in the mechanical load on the diaphragm in the two directions of motion. When the acoustic pressure is increasing, the diaphragm must compress the carbon particles, while this is not true when the acoustic pressure is decreasing.

c. Normal transmitter action for an impressed sine wave does not give a symmetrical current wave, the positive halves of the wave being greater than the negative halves. This indicates the generation of a second harmonic of the impressed wave.

For a number of years, all telephone transmitter designs made use of the mechanical resonance principle to secure increased power output, the response usually being peaked at around 1000 cycles per second. In the more recent designs, an effort has been made to avoid resonance within the voice frequency band with a resultant improvement in quality.

Receivers - The telephone receiver consists essentially of a soft iron or alloy diaphragm, placed in a steady magnetic field and subject also to the influence of a varying magnetic field set up by the voice currents. The steady field is usually supplied by a permanent magnet having soft iron or alloy pole pieces on which the coils carrying the voice currents are wound. With no voice current flowing, the diaphragm, magnetized by a permanent field, is slightly bowed toward the pole pieces. When alternating current flows through the voice coils, the field strength is alternately increased and decreased, and the diaphragm responds to these variations in field strength by moving closer to, or farther away from, the pole pieces than its rest position. As a result, an acoustic pressure wave is set up, reproducing more or less exactly the wave form of the electrical signal. Without the field produced by the permanent magnet, the diaphragm would be attracted by increased current regardless of direction and would therefore respond at twice the frequency of the impressed electrical wave.

As in the case of the transmitter, departures from the ideal design result in distortion, and the wave shape of the sound output is not identical with that of the impressed electrical wave. Distortion may arise because of mechanical resonance or different modes of vibration of the diaphragm and also because of the electrical design of the receiver. The newer receiver designs, such as the HA1 and U1, are largely free from the resonance effects which were deliberately introduced in former designs to obtain increased efficiency at some frequencies. The efficiency of the receiver as a converter of electrical energy to sound energy is relatively low - of the order of a few per cent.

Induction Coils - The induction coil is a transformer whose basic function is to provide an efficient means of coupling the transmitter and receiver units to the line. This is accomplished through suitable impedance matching and the provision of anti-sidetone circuits.

Types of Telephone Circuits - Sidetone is the sound of the talker's voice heard in his own receiver. It results from a transmission path between the transmitter and receiver. This effect causes the talker to lower the level of his voice and thus reduce the level of speech to the distant end, impairing the transmitting efficiency of the telephone set. Room noise picked up by the transmitter and reaching the receiver by the sidetone path impairs the receiving efficiency of the set.

A sidetone type circuit is one in which substantial power is dissipated in the local receiver when the transmitter is energized either by a speech wave or by local room noise. There are 54 possible ways in which sidetone type circuits can be assembled in practice, all of which are essentially obsolete today.

In the transmitting condition the transmitter current does not directly enter the receiver path in the sidetone reduction circuit, thereby reducing sidetone. Also the incoming speech currents do not enter the receiving winding of the induction coil directly and this increases the receiving efficiency somewhat.

There are over 500,000 possible combinations of the elements making up the anti-sidetone circuit. Many of these are impracticable for one reason or another. After having used the anti-sidetone circuit for many years in operator telephone circuits, one circuit was selected for station application beginning about 1930. The essential difference between this circuit and the sidetone circuit is the inclusion of a relatively high resistance third winding and balancing network in the induction coil connection which is bridged across the receiver. The anti-sidetone circuit reduces sidetone on the average of about 10 db. Very few sets remain in plant which are not of the anti-sidetone type.

<u>Handsets</u> - Although handsets were used very early in the business, they were not particularly successful, and development in the United States was concentrated on the desk stand type of instrument. By 1927 the design problems of maintaining approximately the same efficiency in all positions had been solved sufficiently that an anti-sidetone handset was introduced on a restricted basis. This set employed a No. 395 transmitter, which had a tea cup shaped chamber to hold the carbon granules, and a No. 557 receiver. The No. 395 transmitter aged rapidly and was soon withdrawn; some No. 557 receivers are still in use.

The completely redesigned 300-type combined hand telephone set with the ringer in the base was introduced in 1937. This set included the F1 transmitter which had become available in 1934, but the No. 557 receiver was replaced by a new type coded HA1. The result was a combined transmitting and receiving effective improvement of about 10 db.

The F1 transmitter had an improved frequency response and was more easily maintained. The HA1 receiver had a much flatter frequency response than earlier types.

In comparison with earlier telephone sets, whose components were designed at different times, the new 500-type telephone set has the distinction of being the first complete station set to be designed as an integrated unit. With all of its components designed to work with each other and embodying the latest technology, the new set is superior to its predecessors.

A primary objective of the new set was to raise the level of transmission (transmitting and receiving) on long loops. Such an improvement in transmission would make it possible to take further advantage of smaller gauge cables and also to extend the subscriber loop supervision range.

In order to obtain the maximum benefit of the 10 db volume improvement in transmitting and receiving (divided approximately equally), two important features were required in the new set. An equalization arrangement is used to provide full volume output on the long loops and to automatically decrease this level to avoid crosstalk as the loop becomes shorter in length. An improved sidetone balance is necessary to offset the increased efficiency and sensitivity of the new transmitter and receiver units.

The T-1 transmitter provides increased modulation efficiency by changes in size and shape of the unit, a transmitting gain by shortening the handle, and an improved low frequency response.

The U-1 receiver is of the new ring-armature type instead of the conventional bipolar receivers of the past. With this design about 5 db improvement in receiving is obtained, and the high frequency response is improved.

CLASSIFICATION OF TRANSMISSION SYSTEMS

There was a time when transmission systems could be classified simply as exchange or toll. A steady increase in demands for service and ever enlarging areas of community interest have resulted in a telephone plant in which this simple division is rapidly losing its original significance. However, the words "exchange" and "toll" are so ingrained in our terminology that we still consider plant as being "exchange area" or "intertoll", without regard as to whether "toll" charges are collected for its use.

"Exchange Area Plant" is composed of three types of circuits:

a. "Local Loops" are lines radiating from a local central office and terminating in station instruments.

b. "Interlocal Trunks" are facilities that interconnect local central offices, without giving access to the nationwide switching network, and which can be further classified as:

"Direct" - those directly connecting two local offices,

"Tandem" - those connecting a local office with a tandem office,

"Intertandem" - those interconnecting two tandem offices in a metropolitan area.

c. "Toll Connecting Trunks" - Recording-completing, toll switching, and trunks of similar purpose that give access between a local office and the nationwide switching network. This class of circuit has recently acquired the name of "terminal link".

"Intertoll Trunks", frequently called "intermediate links", make up the balance of the plant devoted to message service. They are the circuits which tie toll centers together and form the backbone of the nationwide switching network.

EXCHANGE AREA SYSTEMS

Traditionally local plant has been characterized by its relative electrical simplicity. However, this portion of the plant represents about eighty percent of the Company's investment in lines and equipment, and this large investment is a prime target for the economies inherent in mass produced electronic equipment. The E-type repeater is finding wide application in the trunk plant. A short hall trunk carrier system is under development. The M1 and P1 carriers have been made available for long suburban lines. Negative impedance loading and a cheap subscribers' carrier system for local cable loops are little more than dreams today, but the development of new instrumentalities which will decrease both losses and costs is a certainty.

Loop Facilities

Today the majority of subscriber loops are pulp paper insulated copper pairs in cable. The conductors are 19, 22, 24, or 26 American Wire Gauge. Limited use has been made of cables with aluminum conductors, and any appreciable tightening of the copper supply will probably bring a swing to this material.

Cable with polyethylene insulation on the conductors has been introduced recently. Unlike paper, polyethylene is impervious to water, so that the integrity of the cable sheath is relatively unimportant. This property permits considerable economy in splicing and the use of a series of inexpensive cable terminals of radical design. Polyethylene insulated cable should find a broad application, particularly in distribution plant.

Increased office supervisory ranges and improved station instruments have permitted the use of a high proportion of fine gauge cable — the higher attenuation of the small conductors being offset with loading. H44 loading has been used to a limited extent. However, H88 loading is generally used today, because of its more favorable loss and impedance characteristics.

Some open wire is used for local loops, particularly in rural areas.

The wire is usually 109 mil high strength steel, although 083 steel and the 080 and 104 mil sizes of both copper and copper-steel are used in lesser amounts.

A new sheathless, polyethylene insulated, self-supporting, 19 gauge cable, in 6 and 16 pair sizes, called "B Rural Distribution Wire", has been made available. It can be used as a substitute for 109 steel open wire or small size cable.

Type M Carrier - The M1 carrier system was designed to bring service to subscribers in sparsely settled areas over rural power line conductors. It has also been used to derive additional circuits on rural telephone lines without stringing additional wire. The system has a usable maximum of five channels, each channel being a party line with up to eight subscribers. Thus one system may serve as many as forty rural subscribers.

Channels are amplitude modulated with both sidebands and carrier transmitted. Each telephone channel requires three one-way carrier channels, one transmitting from the central office to the subscriber (carrier frequencies 150 to 230 kc), and two for transmitting from the subscriber to the central office (290 to 420 kc). One of the latter channels is used for reverting calls; that is, for calls to another party on the same telephone channel or party line. In general, excessive crosstalk at the high carrier frequencies used restricts the use of the system to one system per open wire lead. Excessive attenuation of these frequencies requires locating the central office terminal at the open wire-cable junction pole in those exchanges having long entrance cables. Both office and subscriber's terminals are AC powered.

Two modifications of the M system have been made to adapt it to other services. The M1A provides up to five short-haul two-way ringdown trunks. The M1B is for use between a community dial office and the operator office on which it homes.

Type P Carrier - The P1 carrier system is intended for rural subscriber telephone service. It will provide service of the type and of a quality comparable to, or better than, that provided in rural areas on voice-frequency facilities. It will operate over exchange cable and open wire in rural plant served by either dial or manual common battery offices. The carrier system provides up to four two-way channels superimposed on one pair of line conductors, in addition to the physical voice-frequency circuit. The channels may be applied in units of one to four at a time, with as many as 18 to 22 channels applied to a two-crossarm open wire lead, depending on the characteristics of the lead and on the type of P1 arrangement used. Each channel will serve a maximum of eight subscribers. Ringing arrangements are provided for lines with 1-, 2-, or 4-party selective service or for 8-party semi-selective or divided code service. Thus, a single pair with four carrier channels may serve a total of 40 subscribers, 32 by carrier plus eight on the voice-frequency physical facility. One terminal is arranged for rack mounting in the central office and the other for pole mounting along the lead. Other pole mounted equipment includes repeaters and filters, to separate and bypass voice and carrier circuits.

Double-sideband amplitude modulation is used. Each channel employs two transmitted carriers, one for each direction. Carrier line frequencies range between 12 and 96 kilocycles and are spaced at 12-kc intervals as shown in Figure 6-2. Three frequency plans are provided. The stackable arrangement

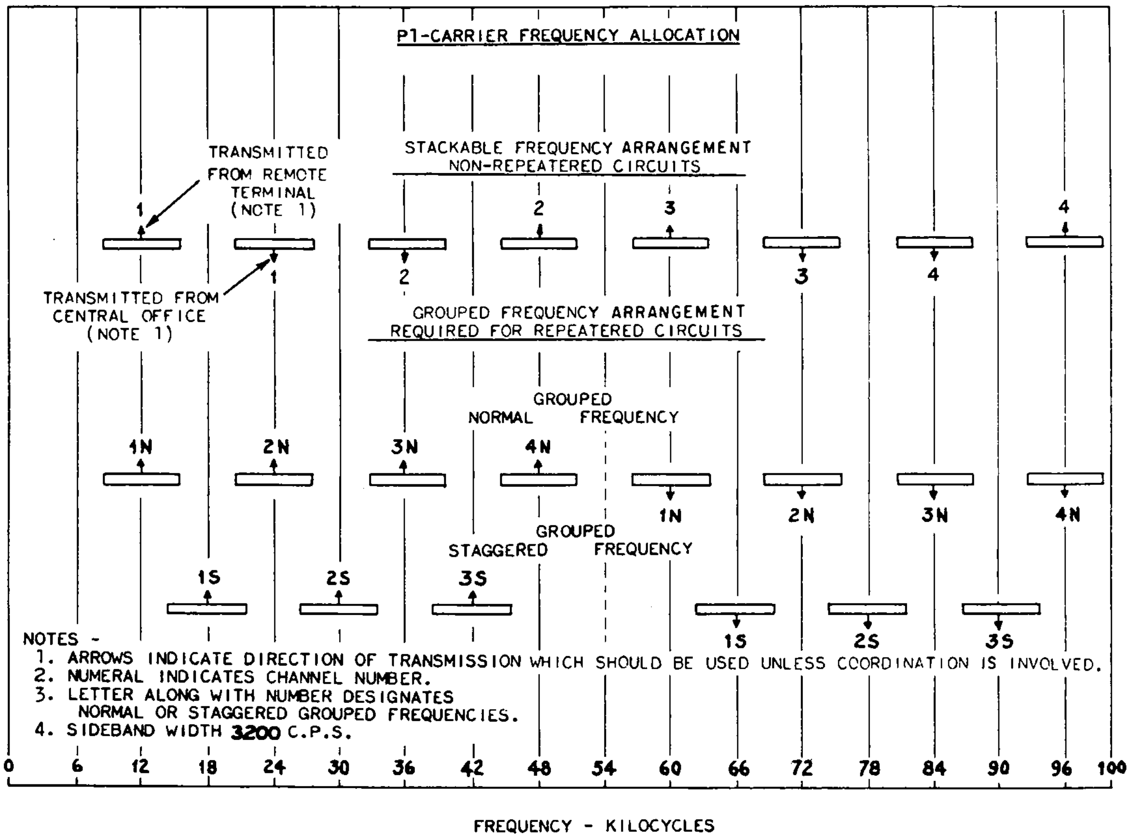


Figure 6-2.

permits longer carrier frequency spans with the lower frequency channels than the other two plans. However, it prevents the use of repeaters on any system on the lead. Both grouped arrangements are for use with repeatered systems. Repeaters are required on lines having bare line attenuation in excess of 30 db at the controlling frequency. The combination of the grouped normal and grouped staggered frequencies gives improved crosstalk performance on leads carrying more than one system. Further improvement can be obtained by arranging the open wire in accordance with the "R1C Transposition Scheme". This is a modification of the R1 Scheme in general use on exchange open wire plant.

Like the N and O toll carrier systems, the P1 system has compandors as an integral part of the terminal equipment. Each compandor consists of two parts, a compressor circuit in the transmitting path and an expandor circuit in the receiving path. These two circuits respond to the incoming speech signal in such a way that the range of signal levels is reduced by a ratio of two, and the average signal level is raised on the carrier frequency line. As indicated in Figure 6-3, the compressor and expandor working together produce no net

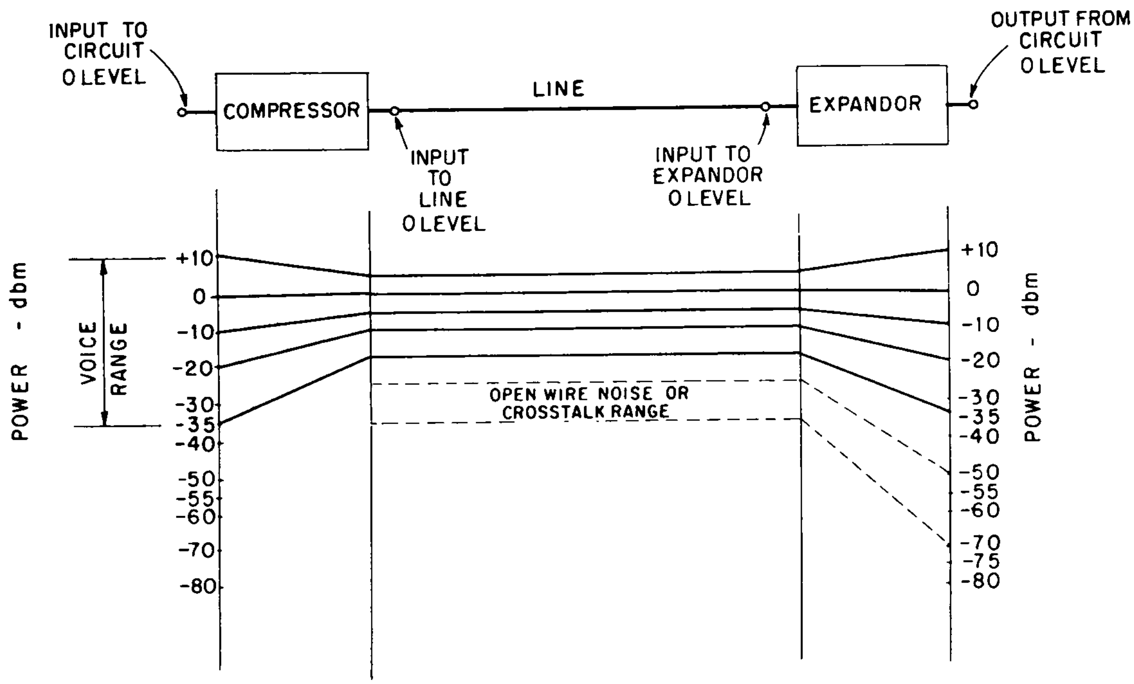


Figure 6-3. Level Diagram of Compandored Circuit.

effect on the speech transmitted. But they effectively reduce noise and cross-talk to about 20 db below the value which would result if the system were not provided with compandors. (A more complete description of the compandor and its operation will be found in the Carrier Practices, AB25 Series, dealing with the N, O, and P systems.)

Every opportunity for cost reduction has been exploited in the design of the P1 system, consequently it has several novel features. The equipment uses transistors rather than electron tubes. Components are mounted on several cards with "printed" wiring. Nine of these cards plug into a pre-wired frame to make a channel terminal. The channel frequencies and signalling arrangement are determined by the cards selected for use. This plug-in principle simplifies engineering, installation, and maintenance of the system.

Both office and remote terminals operate on 22.5 volts dc. Power for the office terminal is supplied from the central office battery through dropping resistors. The remote terminal can be powered by either a small rectifier and storage battery or by air-cell batteries.

Exchange Area Trunk Facilities

In sparsely settled regions, short-haul toll carrier systems and voice frequency open wire are frequently used for toll connecting trunks. However, in metropolitan areas these facilities usually are not economical. As a result, the majority of interlocal and toll connecting circuits are operated over voice frequency loaded cable. Today 19 gauge is the heaviest copper placed for this purpose. The need for 16 and 13 gauge has been eliminated by the availability of cheap repeaters and longer office trunk ranges. Improved instrumentalities should virtually eliminate even 19 gauge requirements in the near future.

Many loading systems have been used in the past, but for reasons of economy and flexibility a few spacings and coil inductances have been chosen as standard. Of these B-88, B-135, H-88, and H-135 have enjoyed the most extensive use. H-88 is usually selected for new construction today, particularly for circuits to be equipped with E-type repeaters.

<u>E-Type Repeaters</u> - Voice-frequency repeaters have been used to overcome the attenuation of long transmission lines for over forty years. Until recently, repeaters were all of the hybrid type. That is, hybrid circuits were used to derive the one-way paths required by conventional vacuum tube amplifiers. The hybrid type repeater is generally not suitable for use in the exchange area for two reasons: It is complex physically and therefore expensive, and it will not pass dc supervisory and dialing signals without auxiliary equipment. In 1949, a new repeater (coded the E1) was made available which does not have these shortcomings. Although the amplification of the E1 is materially less than that obtained with hybrid type repeaters, it is adequate for most local trunk requirements.

The E1 repeater is radically different from its predecessors. It does not break the dc continuity of the line, and it uses one amplifier for both directions of transmission. The device is composed of three principal elements:

a. A transformer, which is cut in series with the line and serves as both input and output transformer for the amplifier,

b. A dual triode vacuum tube, arranged as a grounded grid push-pull amplifier with both positive and negative feedback,

c. A gain adjusting network, which is connected between the plates of the amplifier tube to control the gain-frequency characteristic of the repeater and the impedance that it presents to the line.

The line windings of the transformer have low resistance and inductance and therefore cause only a small loss in the dc and low frequency signals used in supervision, pulsing, and ringing. Under favorable conditions, the repeater has a maximum practical gain to speech signals of about 10 db.

In spite of its novel circuitry, the operation of the E1 can be described in the conventional manner, by tracing currents and potential changes. A good explanation will be found in double numbered BSP A804.486/AB22.153.

Transmissionwise, it is convenient to consider the amplifier as an impedance converter, which makes the positive impedance of the gain adjusting network appear as a negative impedance coupled in series with the line by the transformer. For this reason, the E1 is frequently called a "negative impedance repeater". Negative impedance may be an unfamiliar concept, but its nature becomes apparent when compared with the more common positive impedance.

When current passes through a positive impedance, a voltage difference is developed across the impedance. This voltage drop has a value IZ in accordance with Ohm's law. The voltage will be directly proportional to the current, as long as the impedance is not changed. Further, the polarity of this voltage drop will be such that it will tend to oppose the flow of current through the impedance. The impedance could be replaced with a generator having the same potential and polarity as the voltage drop without altering the flow of current in the circuit.

A negative impedance also produces a voltage across its terminals which is proportional to the current which it carries. However, this voltage will have a polarity that aids the flow of current. So a negative impedance will cancel the opposition to current flow offered by a positive impedance in series with it. It is in this way that the E1 repeater overcomes a portion of the attenuation of the transmission line to which it is connected.

A discussion of how the E1 repeater produces a negative impedance would be too lengthy for presentation here. The subject is treated in detail by J. L. Merrill in the January, 1951 issue of the Bell System Technical Journal. The negative impedance concept is introduced here because it leads to a consideration of the E1's most severe limitation.

Any element of a transmission system that does not terminate the adjacent section in its characteristic impedance will cause reflections or echo. We have seen that the equivalent circuit of any transmission line is a T-network. Therefore, a connected device that is not to be a source of reflections must have an equivalent circuit with both a series and a shunt component. Since the E1 is in effect only a negative impedance in series with the line, it is inherently a source of echo. This unfortunate characteristic has generally restricted its use to interlocal trunks where the echo problem is usually less critical. The degree of impedance match required in toll connecting trunk applications usually cannot be achieved with the E1 operating at any useful gain.

This limitation brought about the introduction of two new negative reactance repeaters in 1954, the E2 and E3. The E2 is electrically the same as the E1 and differs only in equipment arrangements. It has been miniaturized and produced as a plug-in unit. The result is a device that is cheaper to manufacture, install, and maintain, and which requires less building space. From the transmission viewpoint, the E2 is a vast improvement, because center taps are provided on the line windings of the transformer to permit the connection of a shunt element. (A limited number of E1's have been equipped with a center tapped transformer and coded E1A.)

The E3 is identical to the E2 in external appearance, to the extent that the same pattern of die-cast chassis is used for housing both repeaters. The circuit of the E3 is materially different from that of the E1 and E2, but it performs the same function. It makes the positive impedance of its network appear as a negative impedance between the line terminals of the repeater. However, this negative impedance is designed to be bridged across the line. Normally this connection is made between the center taps on the line windings of an E2. Such a combination is termed an E23 or ET repeater.

The combined E23 has the shunt impedance which was lacking in the E1 repeater alone. The gain adjusting networks of the two repeaters can be strapped to give the combination an image impedance that approximates the impedance of any adjacent line section. Under this condition, the E23 can be viewed as an artificial transmission line having an impedance which matches that of the real circuits with which it is associated, but having a negative attenuation constant which replaces some of the energy lost in the real line. Since the E23 can provide appreciable gain without introducing objectionable echo, it is finding increasing application in toll connecting trunks as well as interlocal trunks and special service lines.

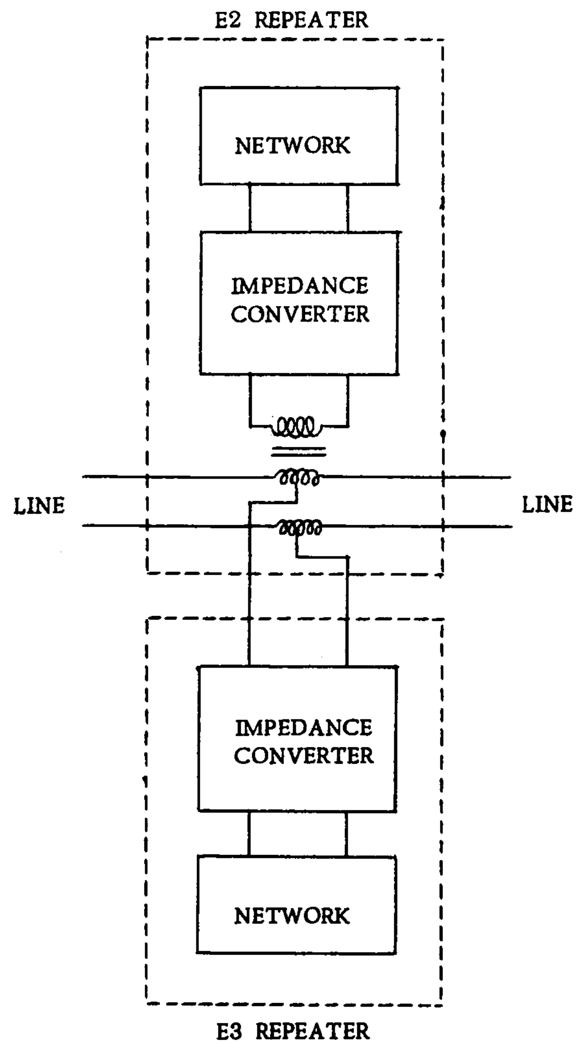


Figure 6-4. Block Diagram of E23 Repeater.

When a negative reactance repeater combination is placed between line sections with different characteristic impedances, it may be desirable to bridge the E3 across the line at one side of an E1 or E2. Such a combination is called an E31 or E32, or in general an EL.

In both the ET and EL combinations, the series and shunt repeater is a separate equipment installation. The repeaters may be directly connected, or the connection may be established by way of an IDF. In either case, the total length of office cabling, including cross connections, permitted between the terminals of the E3 unit and the terminals of either an E1 or E2 unit is 100 feet.

INTERTOLL SYSTEMS

Transmission systems employed for intertoll trunks are characterized by the extensive use of electronic equipment. In fact, long distance telephony became practical only after the invention of the electron tube.

These systems fall into three broad classifications depending upon the frequency at which the voice signal is transmitted — voice, carrier, or radio frequency. We shall treat toll systems under these headings, but when discussing carrier systems we should not lose sight of the fact that a carrier terminal is not a complete transmission system in itself. It is only an instrumentality for channelizing or multiplexing some "base facility". The base facilities are wire (open wire or cable) and radio. A base facility by itself will provide a single voice path; additional paths are obtained by applying a carrier system. In general, the several carrier systems have been designed to work over a particular base facility, but the design engineer's intent has not proved to be a deterrent to the application engineer's ingenuity — H carrier was developed to provide one additional channel on an open wire pair, but it has been used to provide two additional channels on cable pairs carrying twelve K carrier channels — N carrier was designed to work over cable, but it has been used on radio circuits — L type carrier is used to channelize both coaxial cable and microwave radio.

Voice Frequency Facilities

Open Wire Facilities - The wire used is .104, .128 or .165 diameter (in inches) hard drawn copper, or copper-steel in .104 or .128 sizes. There are generally 10 wires per crossarm, supported by wood pins equipped with glass insulators. Wires are usually spaced 12 inches apart except the middle (or pole) pair which is spaced 18 inches apart to provide additional clearance for a lineman working from the pole. Cross-arms are usually spaced 2 feet apart on the poles.

A third circuit known as a phantom is frequently derived by the use of transformers from each two horizontally adjacent pairs at the outer ends of each cross-arm and from each vertically adjacent pole pair. Each such group of two pairs is designated as a phantom group. The four wires of each phantom group are transposed with respect to each other to reduce crosstalk within the group and to reduce noise pickup from adjacent pole lines carrying power circuits. The transposition arrangements of the various phantom groups on a line are generally different to prevent crosstalk among the groups.

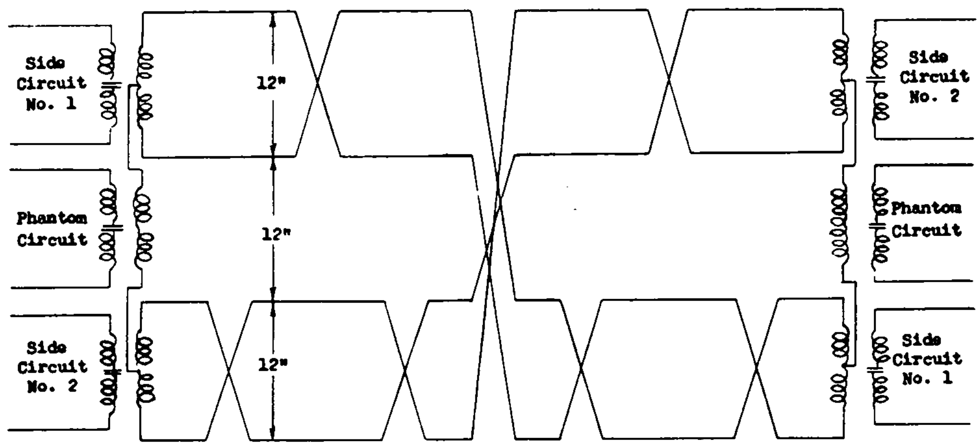


Figure 6-5. Open Wire - Voice Frequency Facilities - One Phantom Group.

Voice frequency repeaters may be spaced at about 150 to 350 miles, depending upon the gauge of wire used in the circuit. Entrance and intermediate cables through built-up communities generally make the actual repeater spacing somewhat less than the values given.

Open wire V.F. facilities are still used to some extent in intertoll plant, but they are rapidly being supplanted by cable or open wire carrier. They are classed technically as one of the better grades of V.F. Facilities due to its high velocity of propagation (about 175,000 miles per second).

Open wire used for carrier systems operating in the frequency range above about 30,000 cycles per second is usually not transposed as phantom groups. The two wires of a pair are spaced 8 or 6 inches apart, and adjacent pairs are separated by 16, 24, or 30 inches. In this type of construction the cross-arm spacing is increased to 3 feet. Wire in this configuration has improved crosstalk performance at the higher frequencies.

Two-wire V.F. Cable Circuits - Annealed copper wire of 10, 13, and 16 gauge were used in the earlier cables but cables placed in recent years have generally used only 19 gauge conductors. Paper (or paper pulp) and dry air or nitrogen gas provide the insulation between conductors.

Phantom groups are derived by twisting two pairs together. Such pair groups are designated as quads. Different rates of twist are used for each pair of a quad to reduce crosstalk within the group. Adjacent quads use different rates of pair and quad twist and the various layers in the cable have different rates of concentric layer twist to reduce crosstalk among quads. Special splicing is employed at certain locations designated as capacitance unbalance test splices to further reduce intra- and inter-quad crosstalk.

A metallic sheath is provided for the entire cable as a shield against the weather and noise from external sources.

Loading coils are employed to reduce attenuation losses. Repeaters are provided at about 35-55 mile intervals to further reduce losses on the longer circuits. However, two-wire V.F. cable circuits 30 miles or more in length are rapidly being displaced by cable carrier facilities for inter-toll circuit usage.

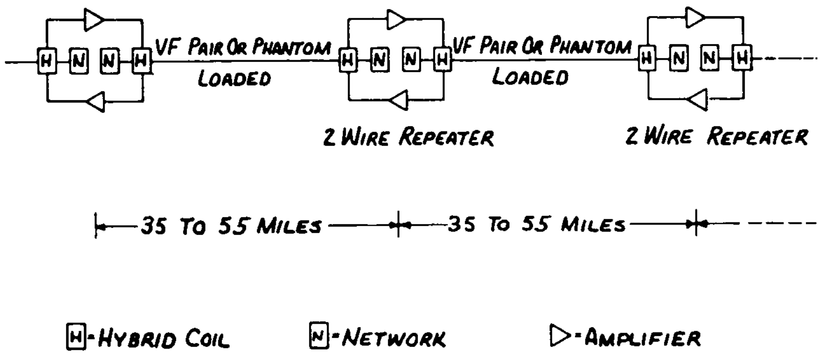


Figure 6-6. Two-Wire Voice Frequency Cable Circuit.

Four-Wire V.F. Cable Circuits - The development of four-wire operation for V.F. cable circuits eliminated the necessity for hybrid coils at intermediate repeater points with consequent reduction of limitations on repeater gain from a singing and echo standpoint.

Groups of quads are generally segregated within separate layers or separate sectors of the cable for each direction of transmission. Intervening two-wire pairs provide some shielding between the groups. This permits the use of higher repeater gains on four-wire circuits without increase of cross-talk between oppositely bound transmission paths. Segregation is also maintained in the central office wiring and cabling.

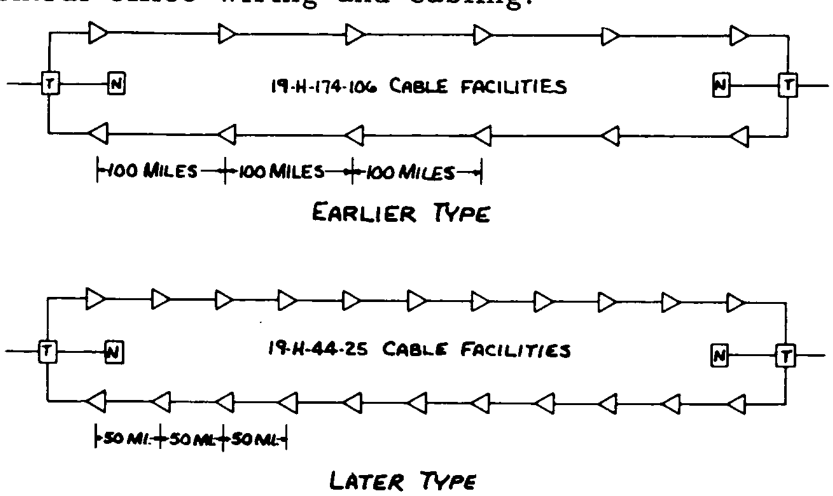


Figure 6-7. Four-Wire Voice Frequency Cable Circuit.

The earlier types of four-wire cable circuits generally used medium weight loading coils at 6000 foot intervals (H-174-106) with repeaters spaced at 100 mile intervals. Such circuits had a velocity of propagation of about 10,000 miles per second. Their minimum loss or maximum length was limited by echo considerations.

Later systems use lighter weight loading coils (H-44-25) with repeaters spaced at 50 mile intervals. The velocity of propagation of such circuits is about 20,000 miles per second. This type of operation permits the use of circuits about twice as long as the earlier type with equal echo limitations.

Four-wire operation is also possible using two-wire nonsegregated facilities having either H-174-63 or H-88-50 loading systems with repeaters spaced at 50 mile intervals. Such operation is usually an expedient to overcome a difficult singing problem. Repeater gains and levels are limited to the same values as used for the paralleling two-wire circuits to avoid crosstalk problems.

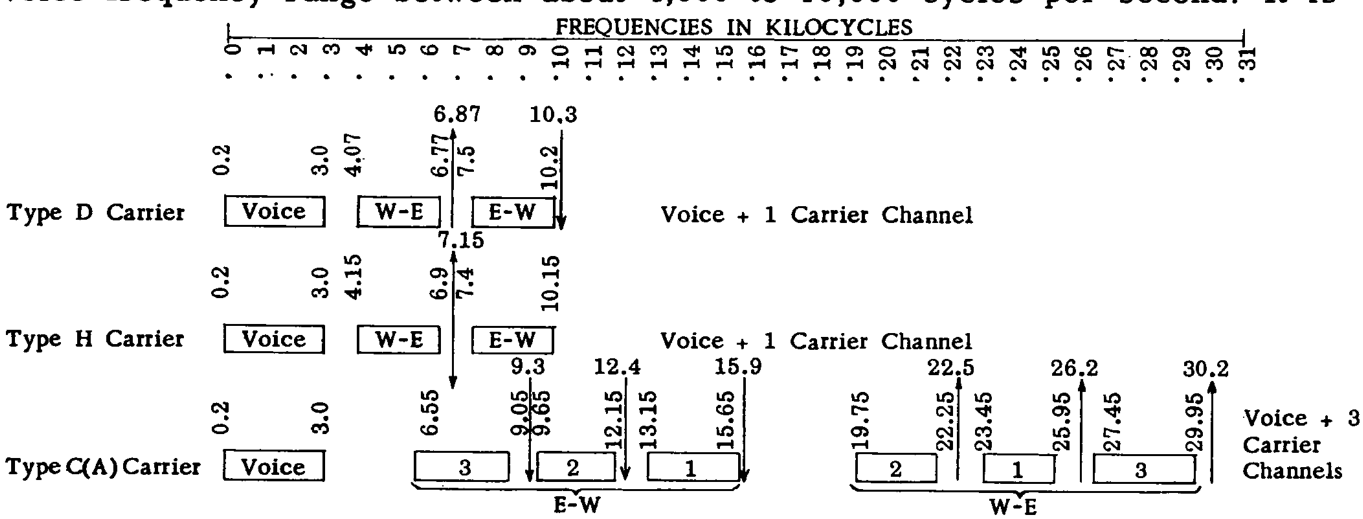
The field of use of four-wire voice frequency circuits is being restricted by the use of cable carrier systems which provide facilities at a smaller cost per circuit mile and permit lower circuit losses with no increase of echo.

Carrier Facilities

Types C, D & H Open Wire Carrier Systems - The 3 channel Type C and single channel Type D carrier systems were developed subsequent to World War I. These systems are used to supplement normal voice frequency circuits on open wire lines.

The V.F. channel band width of the circuits operated over these systems is about 250 to 2750 cycles per second.

As shown on Figure 6-8, the Type D system operated just above the voice frequency range between about 4,000 to 10,000 cycles per second. It is



NOTE: Type "C" Carrier Systems had several differing frequency allocations using both upper and lower side bands. All such allocations were generally contained within the spread of the Type C(A) System.

Figure 6-8. Types C, D and H Carrier Systems Frequency Allocations.

operated on an equivalent four-wire basis using two carriers with the lower side bands for each direction of transmission. However, the system operates on a single pair of wires which may also be part of a voice frequency phantom group.

The Type H system supplanted the Type D using a single carrier with the upper side band for one direction of transmission and the lower side band for the opposite direction of transmission. The frequency range is about the same as the superseded Type D system. Several of these systems can be used on a single open wire line if properly transposed to avoid crosstalk problems.

A Type C system develops three channels operating on an equivalent four-wire basis. It also is applied to a single open wire pair which may be part of a voice frequency phantom group. The systems have various carrier frequency assignments and use both upper and lower single side bands. The various allocations permit the operation of several such systems on a single line and on both pairs of a phantom group without intelligible crosstalk. However, special transpositions are required to reduce the crosstalk volume, unless the various systems are widely separated on the line.

The line frequency range of the Type C systems is from 6.3 kilocycles to 30.2 kilocycles per second. As shown in Figure 6-8, the lower portion of the frequency band is used to transmit in one direction (designated E-W) and the upper portion of band is used to transmit in the opposite direction, with single side bands of separate carriers for each channel in each direction. The carriers themselves are suppressed.

Repeaters are provided for the longer Type C systems. The maximum spacing of the repeaters is from 140 to 180 miles depending on the gauge of line wire used.

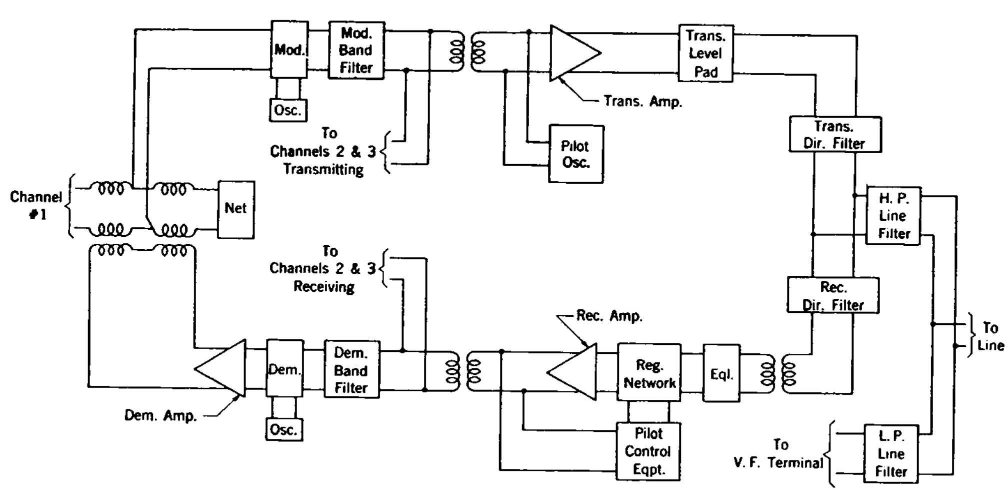


Figure 6-9. Type C Carrier Telephone Terminal.

Type C and Type H systems may be operated on the same line but not on the same phantom group.

Many of these systems are still in operation in the Bell System. However, except to re-use existing equipment, the most recently developed Type O open wire carrier system is generally used for new projects.

Figure 6-9 is a simplified schematic of one channel of a Type C carrier system. The basic arrangements of the components, such as modulators, band-pass filters, directional filters, line filters, etc., are typical of those used in most carrier systems. Hence, circuit schematics will not be given for the other carrier systems to be covered.

Type J Open Wire Carrier System - The Type J carrier system was developed during the 1930-1939 decade for operation on open wire lines. It provides 12 channels per system operating on an equivalent four-wire basis using single side bands for each direction of transmission in a manner similar

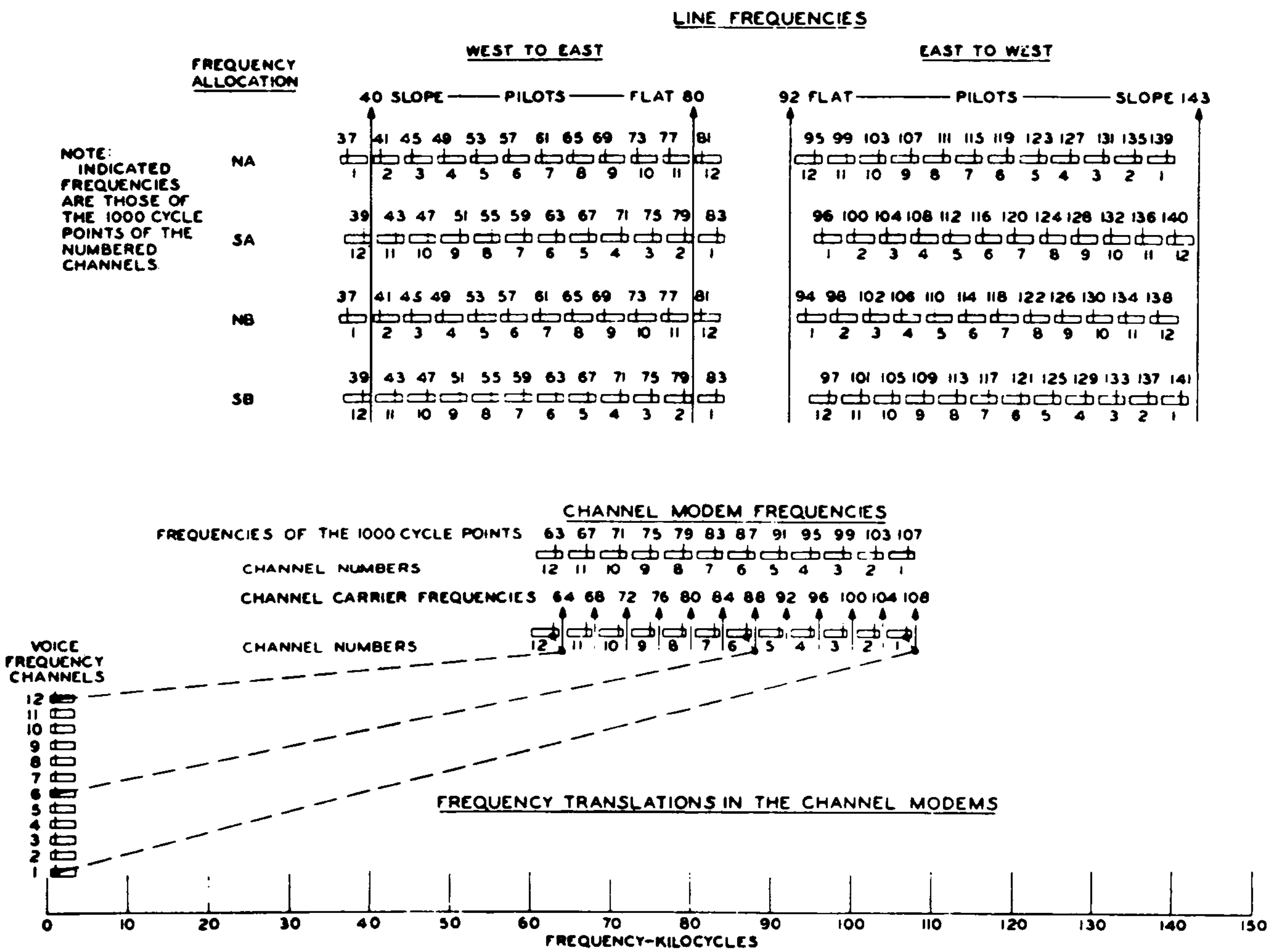


Figure 6-10. Frequency Assignments of the Type J2 Carrier Telephone System.

to the Type C systems. Each system operates over a single non-phantomed open wire pair. Type C systems may operate on the same pairs.

This is one of the systems known as broadband systems using multiple steps of modulation. The basic 12 channel group modulation equipment is the same as is used for the Type K and Type L carrier systems which will be discussed later.

As shown in Figure 6-10, this system is provided with various frequency allocations lying between about 36 KC and 143 KC for transmission on the line, after a second step of modulation.

Type K Cable Carrier System - Figure 6-11 shows the frequency allocations used by the Type K cable carrier system. This system was the first cable carrier system developed for use in this country. Most of the installations were made just prior to and during World War II.

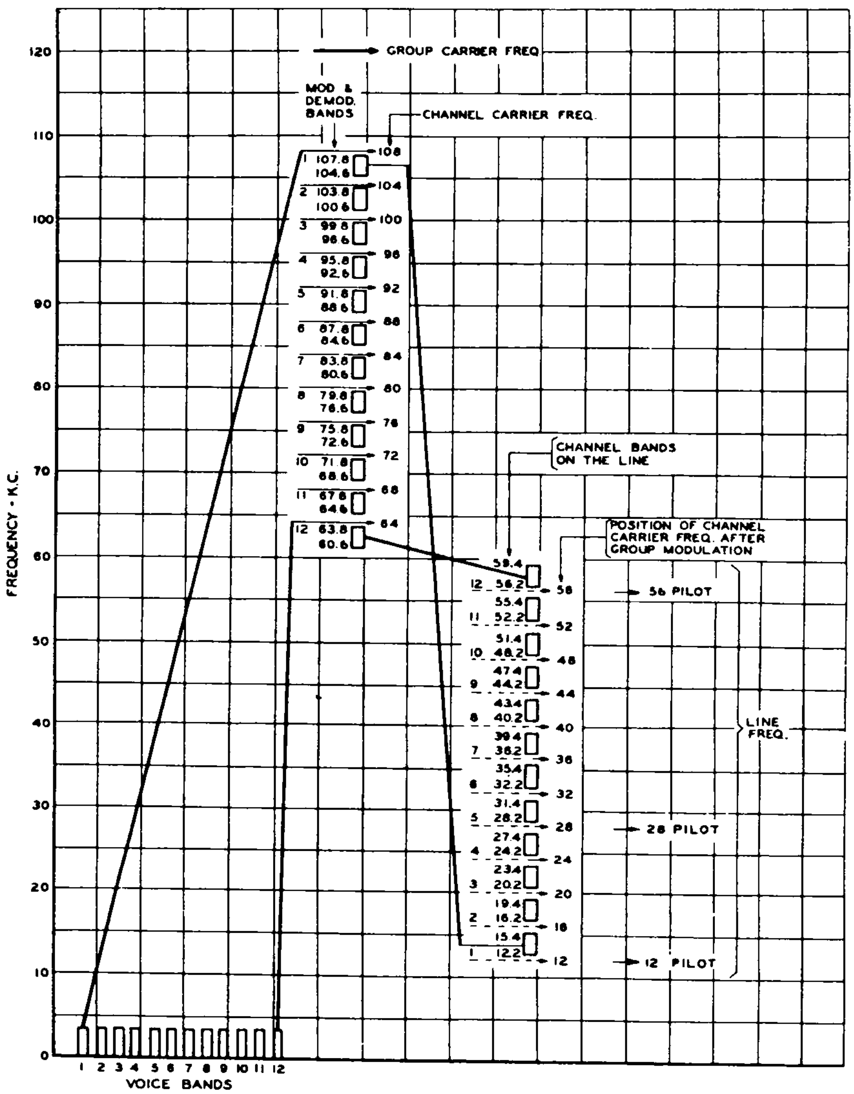


Figure 6-11. Frequency Allocations, Type K Carrier System.

It will be noted that 12 voice frequency channels are individually modulated by carriers spaced at 4 KC intervals from 64 KC to 108 KC inclusive. The lower side bands are selected for each channel by filters with the result that the 12 channels occupy the frequency range from 60 to 108 KC. This is the band occupied after the first step of modulation for transmission in each direction and is likewise the band occupied before the last step of demodulation for transmission in each direction. The 12 channel terminal equipment which modulates the individual voice frequency channels to the 60 to 108 KC range for the transmitting direction and demodulates them from this same range back to voice frequencies in the receiving direction, is identical with that used for the same purpose by the Type J and Type L carrier systems. However, the equipment used for the additional steps of group modulation and demodulation by the J, K, and L systems is different for each system.

The frequency band used for transmission on the cable pairs is from 12 to 60 KC and the same spectrum is used for transmission in both directions. Hence, double steps of modulation and demodulation are required by the Type K system. It should be noted that the second step of modulation or demodulation inverts the numerical order of the channels with respect to the frequency ranges employed.

Since the K system uses the same frequency band in the two directions of transmission, it must be operated on a real four-wire basis. The crosstalk characteristics of paired and quadded cable at K line frequencies are such that the facilities used in the two directions must be physically separated. This is usually done by employing two parallel cables or a single cable which is compartmentized by a metallic shield.

Figure 6-12 shows a schematic layout of a Type K cable carrier system using two paralleling cables. It will be noted that repeaters are spaced at about 17 mile intervals and that every third carrier repeater point may fall at a voice frequency repeater point. The 17 mile spacing is not rigid, but may vary from about 13 to 20 miles depending on the amount of underground and aerial cable along the route and other layout considerations.

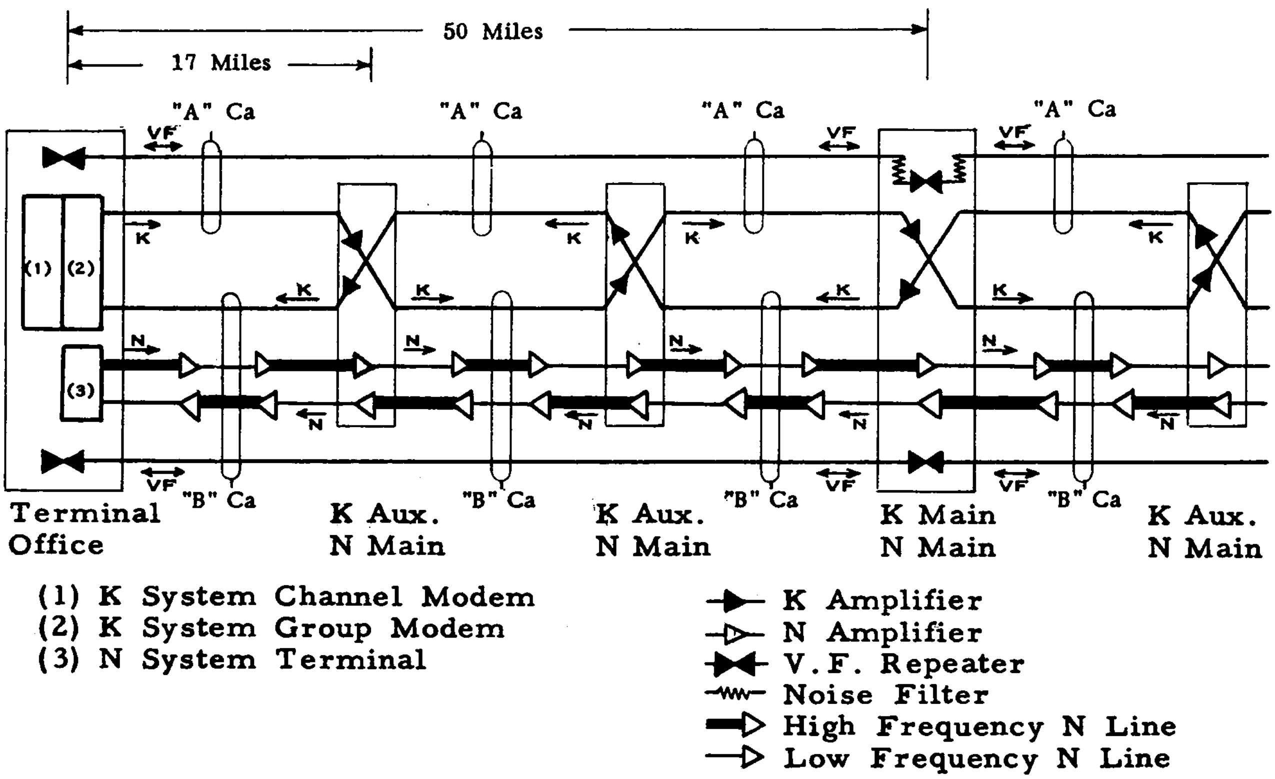


Figure 6-12. General Schematic of K Carrier, N Carrier, and Voice Frequency Systems in Twin Toll Cables.

It will also be noted that pair frogging is used between the two cables at each repeater station so that high level oppositely bound transmission will leave the repeater station in the same cable. Likewise, the low level points will both be in the other cable. This is done to reduce crosstalk between the opposite directions of transmission.

Crosstalk between systems transmitting in the same direction is reduced by the use of special balancing coils interconnecting the various K system cable pairs at certain repeater stations. Intra-system crosstalk among channels is minimized by the use of broadband feed-back type amplifiers at the repeater points.

Choke coils are inserted in the voice frequency pairs of the low level receiving cable at each repeater station. These coils protect the carrier system channels from high frequency noise which might otherwise be induced from the V.F. pairs as the result of the operation of telegraph or other relay equipment located at the repeater stations. The choke coils also provide protection against interaction crosstalk from repeater outputs to repeater inputs by way of the paralleling V.F. cable pairs. Choke coils or filters are also used in V.F. pairs at some points between repeater stations where open wire or cable legs enter the cables. These protect the carrier systems against atmospheric static or other noise which may be picked up on the branch circuits.

Type K carrier circuits have a band width of 150 cycles to 3550 cycles per second. When operated over 5 systems in tandem, the band width is reduced to about 175 to 3350 cycles.

The speed of propagation of Type K carrier circuits is about 105,000 miles per second and they may, therefore, be operated with very low losses from an echo standpoint.

The maximum length of individual K systems is about 1000 miles. Longer circuits up to 4000 miles in length are obtained by operating over several systems in tandem. Frogging of channel assignments is necessary at the intermediate system terminal points to hold noise to acceptable limits on the longer circuits.

Type L Cable Carrier System - The Type L1 carrier system was developed just prior to World War II but most of the installations were made after the war ended. L systems are unique in that an entirely new type of transmission line structure, known as the coaxial pair (or tube) was developed for them. Essentially, this structure consists of a wire surrounded by a concentric copper tube from which it is separated by insulating discs.

The coaxial cable structure is inherently self shielding against crosstalk from paralleling tubes. Intra-system crosstalk is held to a minimum by the use of broad band feed-back type amplifiers. Steel tapes are wrapped around each coaxial tube to provide magnetic shielding against noise pick-up from external sources.

Separate coaxial tubes are used for opposite directions of transmission using the same frequency spectrum for both directions. It is, therefore, a true four-wire system. Each pair of coaxial tubes will transmit 600 telephone conversations or two oppositely directed television programs using the Type L1 system. For the newer Type L3 system, each pair of tubes will transmit 1800 telephone conversations or 600 telephone conversations together with two oppositely directed television programs.

The fundamental package of 12 channels per group is the same as for the J and K systems and uses the same type of equipment. As shown by Figure 6-13, a second step of modulation (using separate carriers) is used to group 5 fundamental 12 channel groups into 60 channel packages which are designated as basic super-groups, occupying the frequency spectrum from 312 to 552 KC. Each super-group (except super-group No. 2) is then modulated a

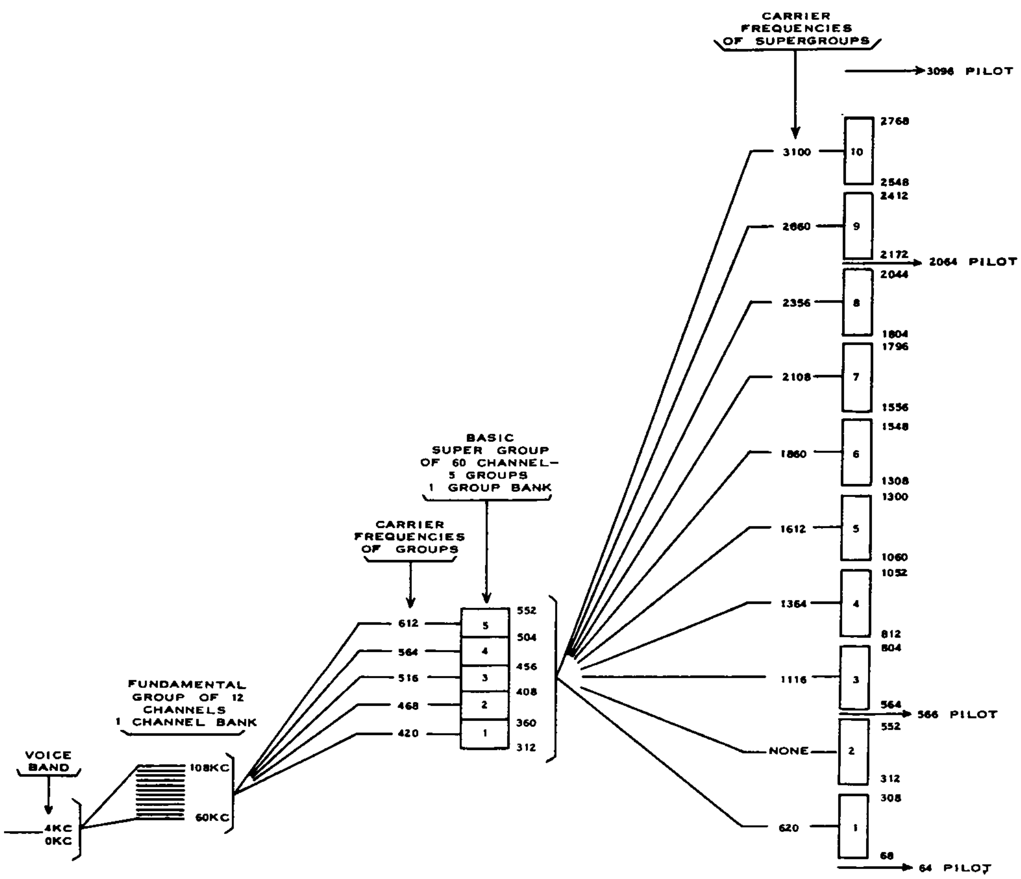


Figure 6-13. L1 Coaxial System Frequency Allocations.

third time using different carriers to provide a total of 600 channels occupying the frequency spectrum from 60 kilocycles to 2.8 megacycles for transmission on the line structure.

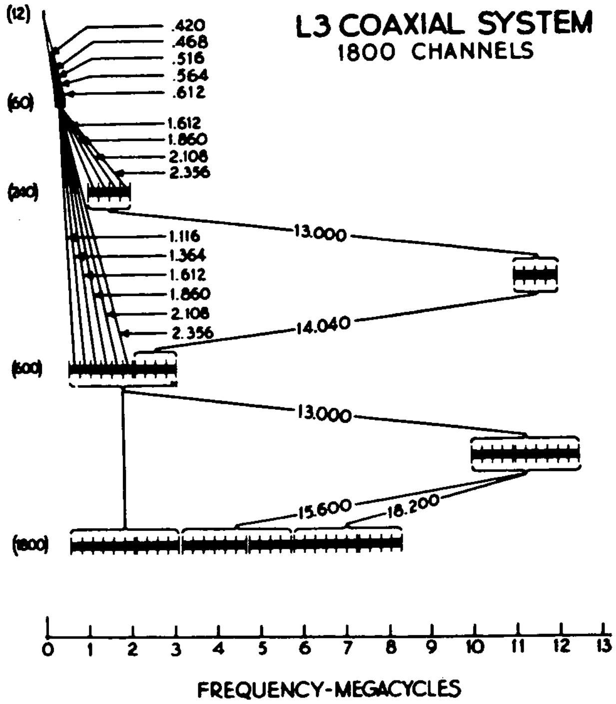


Figure 6-14.

Figure 6-14 illustrates the modulation steps used by the Type L3 system. In this case, the fundamental 12 channel groups and the basic 60 channel super-groups are the same as for the L1 system. Six super-groups are then each modulated a third time and four other super-groups, designated as a submaster group are modulated in two extra steps to form a 600 channel master group occupying the frequency spectrum from .564 MC to 3.084 MC. One master group of 600 channels is transmitted directly to the line and two other master groups are further modulated in two more steps to make up the entire 1800 telephone channel systems using the frequency spectrum from .564 MC to 8.353 MC.

Figure 6-15 illustrates the spectrum assignments when the L3 system is used entirely for telephone circuit channels and also when used in part for both telephone and television transmissions.

Type L1 system amplifiers are spaced at about 7.5 to 8 mile intervals along the cable route and at about 4 mile intervals for the L3 system.

Type L telephone channel circuits are equivalent to Type K system circuits from the standpoint of minimum obtainable loss consistent with echo limitations.

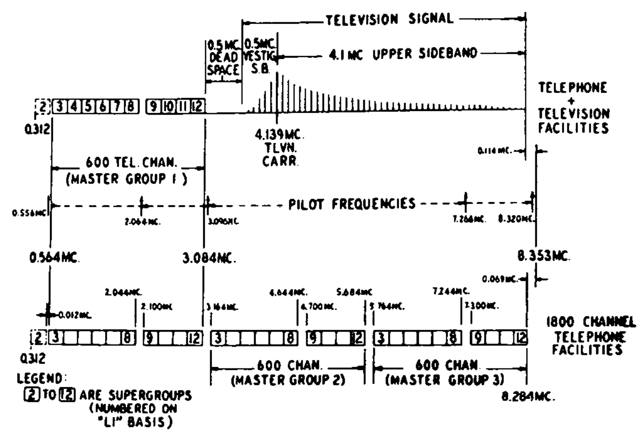
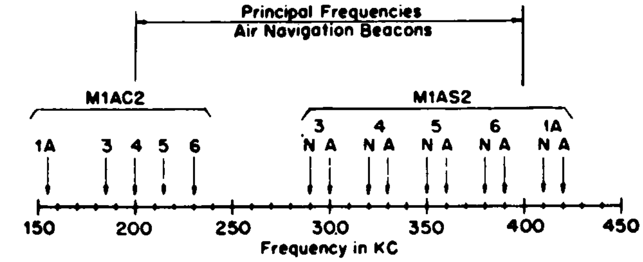


Figure 6-15. L3 Coaxial System Frequency Allocation.

<u>Type M1A Open Wire Carrier System</u> - The Type M1A carrier system is a modified form of the Type M1 rural subscriber carrier system developed during the post World War II period to provide rural exchange service over power or telephone lines. This system was applied to many toll open wire lines to obtain up to 5 additional intertoll circuits during the periods when material shortages made it necessary to postpone toll cable projects. The use of this system for intertoll circuits was purely a stop-gap arrangement and their use for such service should cease within the near future.



Notes:

1. N Designates Normal M1AS2 Frequency
   A Designates Alternate M1AS2 Frequency
2. Channel 2A discontinued.

Figure 6-16.
Transmitting Frequencies -
M1A Carrier Terminals.

It is a double side band carrier transmitted system operating on an equivalent four-wire basis in the band from 150 to 450 kilocycles.

Only one system may be operated on a single open wire line. Their use is limited to very short circuits up to about 30 miles in length.

The system is subject to interference to or from certain radio signals and can disturb Type N cable carrier systems.

Type N1 Cable Carrier System - The Type N1 carrier system is designed to provide 12 two-way telephone channels on two nonloaded cable pairs for distances up to about 300 miles. Each system uses two pairs in a single cable on a true four-wire basis. Two different frequency bands are used for transmissions in opposite directions to eliminate crosstalk between them. The V.F. bandwidth of each channel is from about 250 to 3100 cycles.

It is a double side band carrier transmitted system. Either single or two step modulation and demodulation is used depending on the frequency band transmitted to or received from the line facilities. The 12 voice frequency channels at the system terminals are always modulated to or demodulated from the 164 to 260 KC frequency spectrum by individual carriers spaced at 8 KC intervals at the channel terminals. The line frequency bands used are 164 to 260 KC (High Group) and 44 to 140 KC (Low Group). Therefore, two types of system terminals are provided, known as "High Group Transmitting - Low Group Receiving" (HGT-LGR) and "Low Group Transmitting - High Group Receiving" (LGT-HGR). The type used depends on the number of repeater sections and other factors involved in the system layout. The second step of modulation or demodulation is, therefore, needed only for one direction of transmission (either transmitting or receiving) at each system terminal. This second step is accomplished on a broadband basis using a 304 KC carrier.

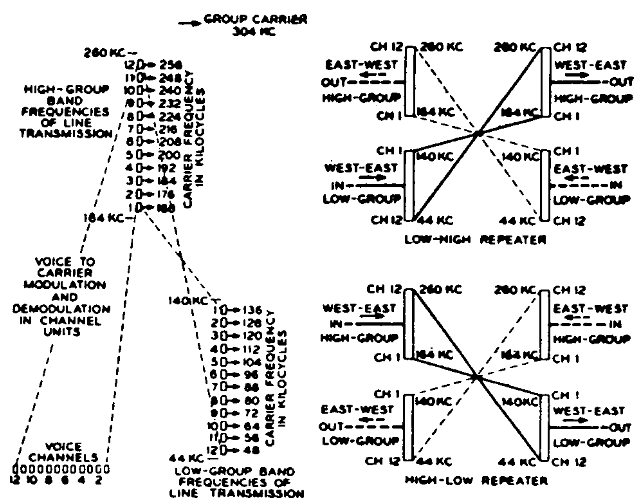


Figure 6-17. N1 Carrier Frequency Allocations for Terminals and Repeaters.

Compandors similar to those in the Type P system are used to compress the range of speech volume as transmitted to the line and to re-expand it to its original range at the receiving end of the line. This process improves the signal to noise and crosstalk ratio for the system and eliminates the need for special crosstalk balancing and noise treatment for the cable pairs. (See Figure 6-3.)

Repeaters for the Type N1 system are spaced at (or built out to) 8 mile intervals when 19 gauge low capacitance cable pairs (quadded or non-quadded) are used. For high capacitance or smaller gauge cable the spacing must be made shorter. Repeater spacings are also reduced when repeaters are located in dial offices to control impulse noise.

Frequency frogging is used at each repeater. This interchanges the frequency groups in each direction of transmission and inverts the frequency sequence of the individual channels. Frogging is accomplished by modulating both groups with a 304 KC carrier. Repeaters along the carrier line, therefore, alternate between two types, "High-Low" and "Low-High", depending upon the frequency band received from the line at the particular repeater station involved.

Frequency frogging eliminates interaction crosstalk around the repeaters through paralleling V.F. cable pairs. It also permits the same repeater spacing to be used for both directions of transmission. The reversal of the channel sequence at each repeater provides automatic self equalization of the channel attenuation losses for two adjacent repeater sections. If there is an odd total number of such sections a fixed attenuation equalizer is used at the system terminals to offset the odd section.

Within the range for which this system was designed very low circuit losses may be obtained with satisfactory echo, crosstalk and noise limitations when used as a part of much longer built-up intertoll connections.

Another new feature of the Type N1 carrier systems, not provided on previous types, is a built-in signalling system using a single frequency above the voice range (3700 cycles per second) in each direction of transmission. These signalling systems are suitable for intertoll dialing and supervision. Other types of signalling may also be connected to the system channels by the use of suitable converters at the system terminals.

Type O Open Wire Carrier Systems - The Type O carrier system has been designed to provide up to 16 circuits on open wire lines which are too short to economically justify the use of Type J systems. This system consists basically of 4 separate 4 channel systems designated as OA, OB, OC and OD. Each system uses a low group and a high group band of frequencies for transmission on an equivalent four-wire basis on a single pair of conductors. The line frequencies for each system are as follows:

	Low Groups		High Groups
OA System	2 to 18 KC	and	20 to 36 KC
OB System	40 to 56 KC	and	60 to 76 KC
OC System	80 to 96 KC	and	100 to 116 KC
OD System	120 to 136 KC	and	140 to 156 KC

The transmitting and receiving voice frequency subassemblies of the Type N1 system are used substantially without modification in the Type O systems. This provides the O systems with the same type compandor and 3700 cycle signalling system as used in the N1 system. The V.F. band width of Type O system channels is also about the same as for Type N1 channels, 250 to 3100 cycles per second.

The Type O system uses single side band carrier channels. Double step modulation and demodulation is used at the system terminals for both directions of transmission. As shown in Figure 6-18, the basic group of 4 V.F. circuits is combined by modulation or separated by demodulation using both upper and lower side bands of two carriers, 192 KC and 184 KC. These

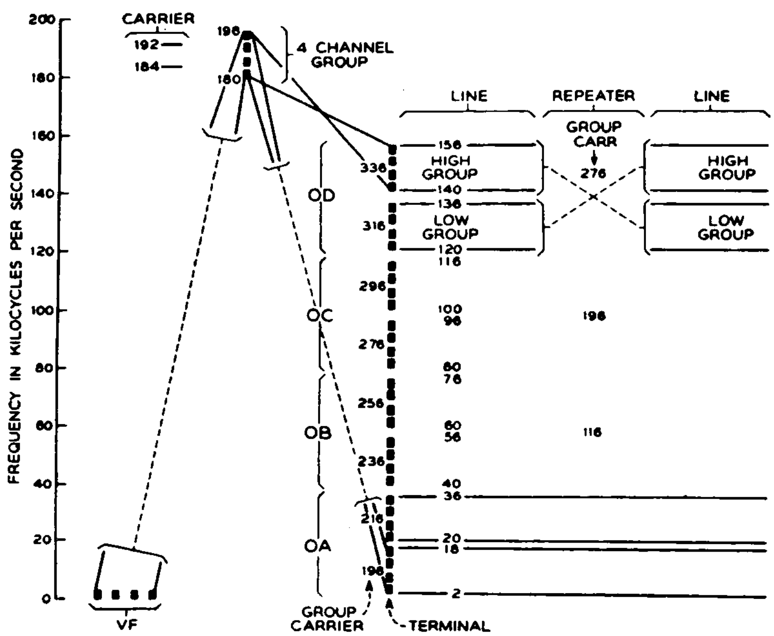


Figure 6-18. Type O Modulation Plan.

carriers are suppressed in the modulators, but a controlled amount from the same oscillators is reinserted for transmission on the line for regulation purposes. The channel group frequencies from 180 to 196 KC are the same for all Type O systems (i.e., OA, OB, OC and OD). Group modulators and demodulators using different group carriers then translate the basic groups to or from their proper positions in the line frequency spectrum.

The Type OA system operates substantially in the same manner as a Type C system. The high group line frequencies are used throughout the system for transmission in one direction and the low group line frequencies transmit in the opposite direction. If all 4 channels of the OA system are used, the V.F. channel on the pair must be discontinued, but some carrier telegraph channels may be added in the spectrum space below 2 KC. If the OA system is operated as a 3 channel system, it may be used as a supplement to a V.F. circuit on the same pair in exactly the same manner as a Type C system.

The OB, OC, and OD systems use frequency frogging at the repeaters in the same manner as for Type N1 cable systems. OB, OC, and OD systems may be used on the same pair as Type C or Type OA systems (but not both) to obtain 12 additional carrier channels.

Two types of repeaters are provided for the O carrier systems. One type is for the Type OA system which does not provide frequency frogging. The other is for the OB, OC, and OD systems which do provide such frogging. The Low-High and High-Low arrangements of the OB, OC, and OD repeater are obtained by using twin unit directional and bandpass filters which are reversible in plug-in sockets. The different group oscillators required for the several allocations are also provided on a plug-in basis.

Repeater spacings for the OA and OB systems are about 50 miles in sleet storm areas and about 100 miles in other areas. The spacings for the OC and OD systems is approximately half the spacings for the OA and OB systems.

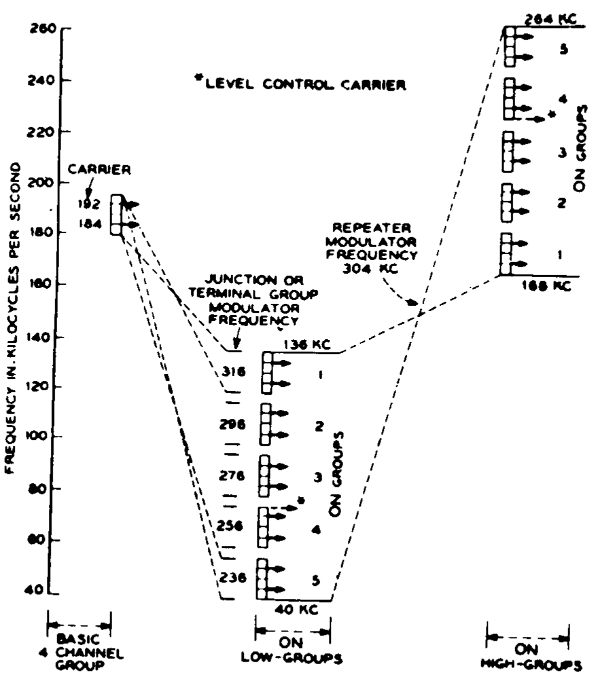


Figure 6-19.
Type ON Carrier Modulation Plan.

Type O open wire carrier circuits may be extended through long toll entrance or toll cables on Type N1 cable facilities by the use of special cable-open wire junction repeaters which translate from the line frequency spectrum of one system to that of the other.

Type O system circuits will operate at very low losses from the standpoints of echo, crosstalk and noise.

Type ON Cable Carrier System - The Type ON cable carrier system is a composite system using Type O carrier terminal equipment and Type N1 repeater equipment. Since the Type O terminal equipment provides for single side band channel operation, it is possibe to obtain 5 basic 4 channel groups (20 channels total) within a line frequency group band width equivalent to that used for the 12 double side band channels of the Type N1 system.

Figure 6-19 indicates the modulation and demodulation steps of the Type ON system and the frequency spectrums used. Note that the basic 4 channel group frequency band is the same as for the O system and the high and low group line frequency spectrums are approximately the same as for the Type N1 system. The low group is 4 KC lower at both ends and the high group is 4 KC higher at both ends.

Radio Facilities

Radio systems as used in intertoll plant are a type of line facility. They serve as an alternative to physical lines such as open wire, cable pairs, or coaxial tubes. Like coaxial tubes, radio systems are one-way facilities. Therefore, twin systems must be used to accomplish transmission in both directions.

For most intertoll applications highly directive parabolic reflector or lens type antennas are used, so as to confine the radio waves to narrow paths similar to the beams of a searchlight. Radio repeater stations are located at intervals of about 25 to 50 miles. At the high radio frequencies employed, the radio path must have at least line-of-sight clearance over obstructions and the curvature of the earth.

Frequency allocations for radio systems cannot be chosen freely by the telephone companies since the radio spectrum is considered a part of the public domain. The Federal Communications Commission makes the general allocations of this spectrum to various types of radio services and its permission is required for each specific assignment within an allocated band.

Since radio systems are line facilities, multi-channel operation is obtained by using the line frequency outputs of carrier system terminal equipments to modulate the radio system carriers. Carrier system applications to radio systems generally result in a greater over-all speed of propagation than when the same systems are applied to physical line facilities. Accordingly, radio system telephone channels are the best that are available from an echo standpoint.

Type TD2 Heavy Route Radio System - This system provides 6 radio channels in each direction of transmission (total - 12 channels). The assigned radio frequency spectrum is from 3700 MC to 4200 MC with 40 MC spacing between radio carriers.

Each radio channel may be used for a one-way television program circuit or an oppositely directed pair of radio channels may be subdivided for telephone circuit usage. This radio system normally uses Type L1 carrier terminal equipment to derive up to 600 voice channels per pair of radio channels. Under some conditions it is feasible to channellize with eight super-groups of L1 and sub-master group 2 of an L3 system to obtain 720 voice channels on a pair of radio channels.

Type TH Heavy Route Radio System - This system is currently under development by the Bell Laboratories to operate with radio frequencies in the common carrier fixed allocation at about 6000 MC. It may be used to supplement TD2 system facilities on routes requiring additional radio facilities, or it may be applied to new routes. Type L3 carrier terminal equipment will probably be used in conjunction with the TH system to derive the telephone and television channel requirements. A new type of broadband antenna has been developed in conjunction with the TH system. This antenna can be used by the TD2, TH, and TJ systems in common.

Light Route Microwave Radio Systems - Development is nearing completion on another new radio system at the Bell Laboratories which has been designated the TJ system. It will operate in the 11,000 MC range. A new arrangement of ON carrier equipment that will accommodate 96 voice channels may find application on the TJ system, or it may be used for short television circuits.

The Laboratories have also made some modifications of the TD2 system in an effort to reduce its cost so that it may be used on some of the lighter routes.

Light route radio system equipment for telephone usage is also manufactured by such companies as:

(1) Motorola, Inc.
(2) Radio Engineering Laboratories
(3) Philco
(4) Westinghouse Electric Company
(5) General Electric Company
(6) Lenkurt

Some of the smaller capacity carrier terminal equipments (such as Type N, Type O, Type ON, and Lenkurt 45BX) have been applied to such systems.

Echo Supressors

Echo suppressors are voice current operated devices which will insert a high loss in the oppositely bound transmission path when speech currents are present in one path of a four-wire circuit. Thus, echo currents are blocked from returning to the talker.

Such devices may cause some clipping of speech syllables, particularly if both parties try to talk at the same time. Likewise, if there are several such devices involved in a connection, lock-up may occur with consequent interruption of transmission.

Characteristics Affecting Use of Intertoll Facilities

There is no simple formula sharply defining the fields of use of various types of intertoll facilities. Over-all economy should determine the instrumentality selected for each installation. Intangible factors may well take precedence over simple dollar calculations. For example, the use of a radio system to parallel an existing landline, rather than to provide a less costly relief of like type, may be justified in some cases purely from the standpoint of continuity of service. Such a decision would be based on the fact that the likelihood of simultaneous failures involving both types of systems is very remote.

Table 6-1 lists the principal toll systems in the order of their velocities of propagation. We shall see in Chapter 7 that echo becomes more critical as the velocity is decreased. Echo is the primary consideration today in determining minimum allowable circuit loss. Other conditions being equal, the nearer the top of the Table, the lower the permissible net loss of the facility.

PREFERRED ORDER OF CHOICE OF INTERTOLL FACILITIES
FROM THE STANDPOINT OF ECHO

Choice	- Facility -
Best (High Velocity)	Radio System Channels (All Types)
↓	Type L Cable Carrier
↓	Open Wire Carrier Systems
↓	Type K, N or ON Cable Carrier
↓	VF Open Wire or 4-Wire Light Loaded Cable
↓	VF 4-Wire Medium Loaded Cable
Poorest (Low Velocity)	VF 2-Wire Loaded Cable

Table 6-1.

Since all types of voice-frequency facilities are gradually being superseded by carrier circuits for intertoll usage, we will confine the following discussion to carrier systems.

Table 6-2 summarizes some general characteristics of Western Electric Company carrier systems in use today. The values shown are for typical installations.

In practice, system lengths are subject to considerable variation. The minimum length is determined by the relative costs of line facilities and terminal equipment. Maximum length is determined by fundamental system design

Type System	Line Facilities Per System	Channels Per System	Channel Capacity Of Typical Route	Nominal System Length (Miles)[5]	Integral Signalling Arrangement	Minimum Convenient Group Of Channels
L3	Two Coaxial Conductors[1]	1800[2]	5400	400 & over	none	60
L1	Two Coaxial Conductors[1]	600[3]	1800	400 & over	none	60
K	One Pair in each of Two Twin Cables	12	420 to 1200	75 & over	none	12
N	Two Cable Pairs or One Quad	12	300 to 900	25-300	E & M Leads	12
ON	Two Cable Pairs or One Quad	20	500 to 1500	50-400	E & M Leads	4
O	One 156 KC OW Pair	16	64-240[4]	15-150	E & M Leads	4
J	One 140 KC OW Pair	12	48-192[4]	125 & over	none	12
C	1/2 of 30 KC OW Group	3	12-48[4]	60 & over	none	3
H	1/2 of 10 KC OW Group	1	4-16[4]	25-150	20 cycle	1

(1) Also applicable to microwave radio relay.
(2) Alternatively 600 telephone circuits and one 4 MC television channel in each direction.
(3) Alternatively one 2.8 MC television channel in each direction.
(4) On a one to four crossarm lead.
(5) Usually not economical below smaller figure; transmission may fail to meet standards beyond larger figure.

Table 6-2. Summary of General Characteristics of Carrier Systems.

and the noise and crosstalk performance of the line facility. Development of systems to work over long distances requires particular attention to regulation, distortion, and system noise problems. Components of the terminal equipment must be manufactured to finer tolerances as the intended length of the system is increased.

The number of systems that can be operated in parallel on a given route is determined principally by the refinement of design and care in construction of the outside plant. This is particularly true of open wire systems. By sacrificing channels and limiting system length, use is frequently made of open wire that is of a grade materially lower than that contemplated when the system was developed.

Table 6-3 lists some of the more common systems in relative order with respect to characteristics which determine their selection for a specific application. (Flexibility indicates the smallest block of channels that can be conveniently dropped off at intermediate offices along the route.) Other pertinent considerations not shown in the Table are:

	Systems Listed in Approximate Order of			
	Ultimate Route Capacity	Line and Repeater Costs per Circuit	Terminal Costs per Circuit	Flexibility
Least	O1	L3	N1	L3
	N1	L1	O1	L1
	K	ON	ON	K
To	ON	N1	K	N1
	L1	K	L1	ON
Most	L3	O1(1)	L3	O1

NOTE:

(1) The line costs for O1 vary over a very wide range, depending on circumstances, and on some routes may be less than for ON or N1 and on others more than for K.

Table 6-3. Summary of Characteristics Affecting Field of Use of Carrier Systems.

a. The system must be capable of providing an acceptable quality of transmission over the distance to be spanned.

b. If existing outside plant is to be employed, it must be made suitable for the proposed system. This work may be an important factor in the cost of a project. Voice-frequency loaded cable must be deloaded for carrier operation. Cable pairs to be used for K carrier require special treatment to minimize crosstalk. K, N, or ON routes may need protection against the influence of noise from external sources. Realizing the ultimate higher frequency carrier capacity of an open wire lead usually entails extensive transposition rearrangements. L3 cannot be substituted for L1 without substantial expenditures for new repeater stations.

c. The proposed system must be compatible with those already in operation on the route. Type J and higher frequency O systems usually cannot be operated on the same lead. Only under the most favorable conditions can N or ON systems be added to a K carrier route without sacrificing several channels per system.

d. If the system does not have suitable built-in signalling features, the cost of the necessary auxiliary equipment must be considered.

e. The type and capacity of available power plants may be an important consideration.

As with the choice between the several types of carrier systems, there is no unique field of use that may be said to be assignable to radio in preference to the construction of land line facilities. Each case must be studied on its own merits, and considerations other than the purely economic ones may be controlling.

SIGNALLING AND SUPERVISION SYSTEMS

In addition to the function of carrying speech information between two widely separated persons, exchange area and intertoll facilities must be equipped to perform certain other functions. These functions are generally designated as signalling and supervision.

> Signalling may be defined as the transmission of the information required to initiate, establish, and terminate a telephone connection.
>
> Supervision refers to those signalling functions which indicate the status of a connection.

The choice of signalling and supervision systems to be used in a given situation is intimately related to the channel facilities which are to be used for the conversation which is to be transmitted.

Ringdown Systems

Ringdown signalling requires the transmission of a signalling current from the calling end of a connection which will cause a visible or audible signal to attract the attention of an operator at the called end. The visible or audible signal thus advises the called operator that a call is waiting to be established. When the called operator connects her telephone set to the circuit and verbally responds to the signal, the originating operator transmits the necessary information to permit the connection to be established. The start of conversation is determined by the originating operator by listening on the connection, and the end of conversation is also determined by listening or by observation of a signal initiated when the subscriber at the calling end hangs up.

Facilities are usually cleared by again initiating the ringdown signal on the facilities from the calling direction and advising the distant operator verbally that the circuit is clear for another call. If the connection involves more than one ringdown link each intermediate operator would likewise "clear" to the next operator, if any, along the connection. Clearance of facilities may also be accomplished in the reverse direction if the operator at the called end of the connection first observes a hang up signal from her subscriber.

Ringdown signalling is rapidly being displaced as the plant is being converted for interconnection by mechanical switching systems.

20 Cycle System - As its name implies this system uses a 20 cycle per second signalling current. It is the earliest form of signalling and uses the same nominal frequency as that used to operate the bells in a customer's telephone set. This frequency is in the same spectrum as that used for D.C. telegraph systems. Therefore, it cannot be used if such telegraph systems are

superimposed on V.F. telephone facilities. If voice frequency repeaters are used along the circuit, the 20 cycle signal is blocked from passing through such repeaters by filter action. In such cases, intermediate ringers are associated with the repeaters to re-supply the 20 cycle signal to the line section following the repeater.

135 Cycle System - Where D.C. telegraph is superimposed on V.F. facilities, 135 cycles is sometimes used as the signalling current rather than 20 cycles. This frequency falls between the upper edge of the D.C. telegraph range and the lower edge of the usable V.F. band (200 - 250 cps). This type of signalling functions in substantially the same manner as the 20 cycle system, except that in some cases, a minor amount of amplification may be obtained through a V.F. repeater thus permitting the occasional omission of an intermediate ringer.

1000 Cycle System - This system uses a 1000 cycle current which is modulated at a 20 cycle rate. Intermediate ringers are not required at V.F. repeater points with this system, since the repeaters will amplify the signal the same as the 1000 cycle components of speech. The 20 cycle-1000 cycle combination is used for the signalling current so that the 1000 cycle components of speech will not falsely operate the ringers at the circuit terminals during the conversation period. This signalling system may be operated over any type of carrier system speech channel and on V.F. facilities which are equipped for superimposed D.C. telegraph operation.

Direct-Current Systems

Direct-current systems are capable of automatically passing signalling and supervision information in one or both directions, depending on the type used. They may also be used to transmit pulsing information which can be used to actuate mechanical switching systems. These systems are applicable only to voice frequency facilities. Three types of d-c systems are available: loop, composite, and simplex.

Loop System - Loop signalling and supervision employs the pair of conductors used for talking. The necessary signalling and supervisory information is transmitted by combinations of three methods:

a. Opening and closing the loop. (i.e., pulsing of current flow)

b. Marginal Currents (i.e., changes in amount of current which flows)

c. Reverse Battery (i.e., changing direction of current flow)

Loop d-c systems cannot transmit information simultaneously in both directions. They are limited to use on circuits over which connections can be established only in one direction. The operating range of d-c loop systems is limited to a maximum of about 25 miles. Therefore, they are seldom used on intertoll facilities.

Composite (CX) System - There are three basic equipment units involved in composite (CX) signalling:

a. Composite sets

b. Composite signalling circuits

c. Pulse link circuits

Figure 6-20 illustrates a pair of composite sets and composite signalling circuits applied at the two ends of a V.F. speech channel. The composite

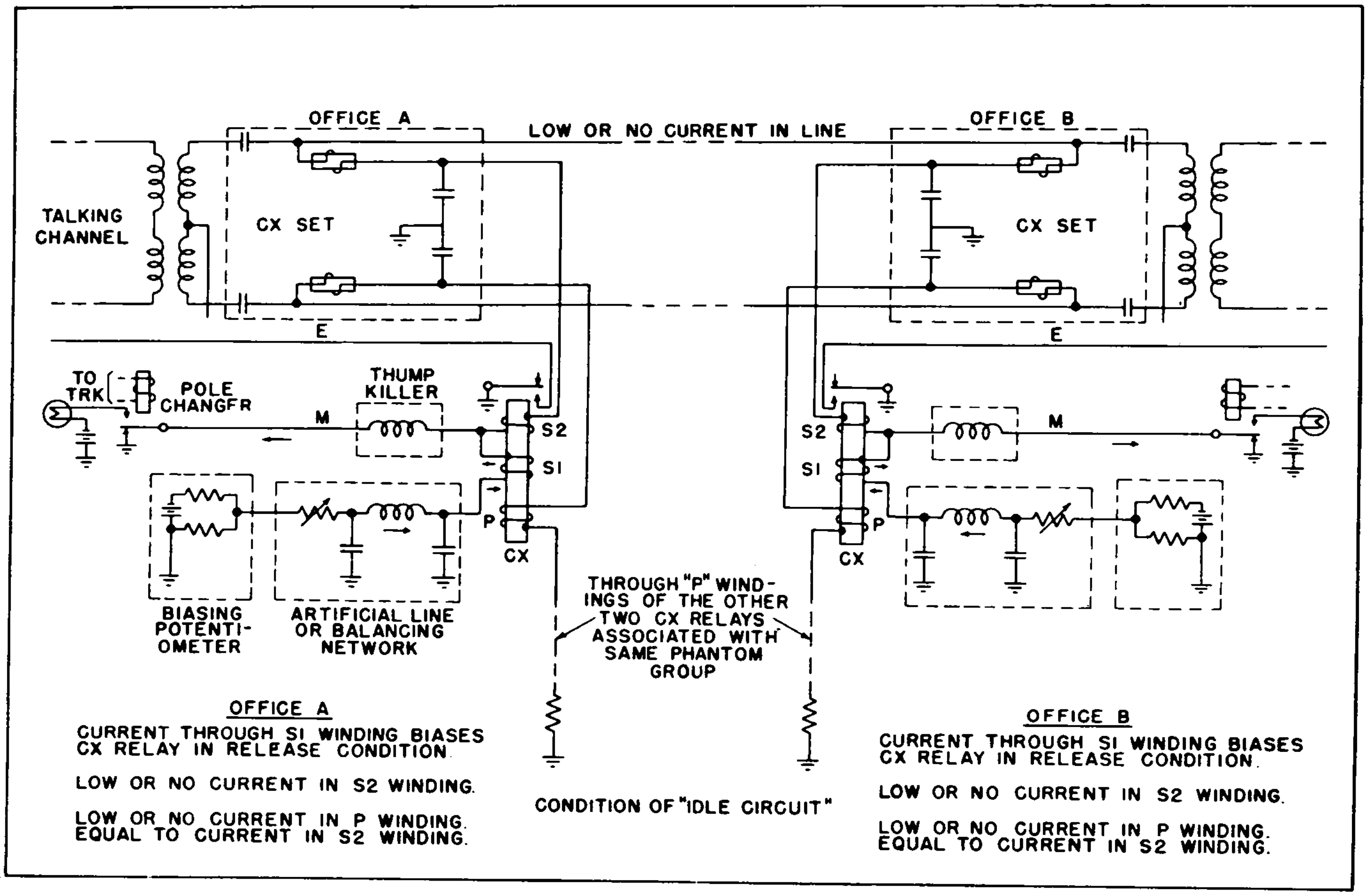


Figure 6-20. Composite Signalling-Principle of Operation.

set used in conjunction with the transformer (repeating coil) at the circuit terminal constitute a high-pass and low-pass filter combination which permits voice frequencies to pass through the repeating coil and blocks d-c and low frequency (below V.F.) pulsing d-c currents from the V.F. circuit terminals. Two paths are provided by the CX set to pass the d-c and pulsing currents from each line conductor to ground via the CX signalling equipment. Thus, each V.F. pair can develop two separate channels for signalling and supervision. When CX signalling equipment is applied to both sides of a phantom group, three of the derived signalling and supervision channels are used for the three V.F. circuits of the group. The fourth channel is used to cancel out the effects of ground potential differences between the two ends of the circuit which might adversely affect the operation of the CX signalling equipment.

Simultaneous transmission of signalling and supervision information in both directions on the same channel is possible with the CX system. This is similar to full duplex telegraph operation from which the CX system was derived. A complete discussion of the operation of the CX signalling equipment will not be attempted here, but attention is directed to the two output leads from this equipment. They are connected to the trunk circuit equipment which utilizes the pulsing, signalling, and supervision information being transmitted. All modern signalling and supervision systems are arranged to develop E & M output leads so that various types of such systems may be interconnected as may be necessary.

Figure 6-21 illustrates two types of pulse link circuits which may be used to transfer signalling and supervision information around intermediate

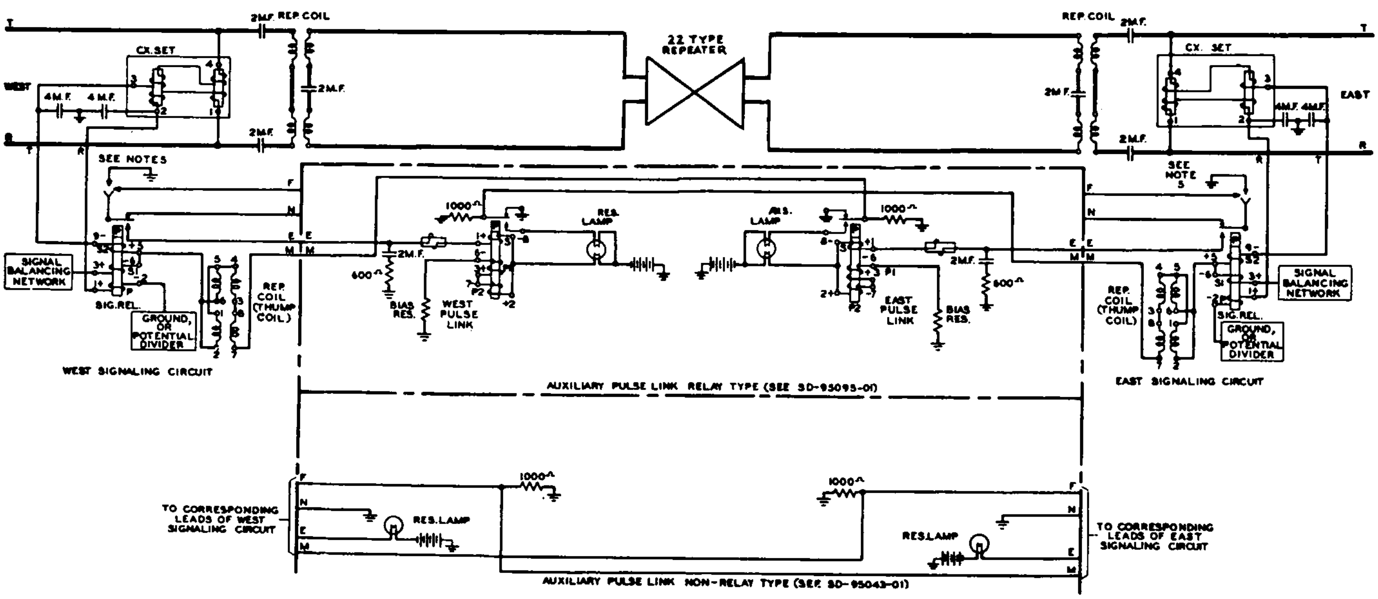


Figure 6-21. Auxiliary Pulse Link Connecting Two Composite Signalling Circuits.

equipment such as transformers (repeating coils) and V.F. repeaters which will not pass d-c or pulsing d-c currents. The type of pulse link equipment to be used in a given situation depends on transmission considerations. Pulse link equipment may also be used to interconnect different types of signalling and supervision systems where necessary.

CX signalling is not satisfactory for circuits more than about 300 miles in length if dial pulsing is applied. This limitation is due to the delay caused by the operation of many relays in tandem which causes excessive pulse distortion. If dial pulsing is not required the CX signalling system may be applied to circuits of considerably greater length.

Simplex (SX) System - The simplex signalling system is essentially the same as the composite (CX) system except that composite sets are not required. The two line conductors are used in parallel for the signalling and supervision channel. The lead to the CX signalling circuit is taken directly from the mid-point of the line transformer (repeating coil). (Refer to Figure 6-20.) Since the earth potential balancing lead is not available, this function must then be obtained by using a separate conductor. However, this separate conductor may be used in common by as many as 5 separate SX signalling channels. Signalling, pulsing and supervision information is blocked from the talking channel terminals, because the voltages they develop across the two halves of the line windings of the transformer cancel each other in the drop (or V.F. channel) windings of the transformer. These voltages act in parallel, however, so far as the CX signalling equipment is concerned. This method of separating the signalling and supervision information from the speech channel information is as effective as the use of composite sets and is considerably less expensive. When SX signalling is applied to phantomed open-wire or quadded cable facilities, it is not possible to derive the phantom circuit. This factor more than offsets the omission of CX equipment and restricts the field of use of such systems. For this reason SX signalling is not frequently used except for very short intertoll circuits and for toll connecting trunks.

Duplex (DX) System - The DX signalling system is similar to the CX signalling system in that it is balanced and symmetrical. However, it differs from CX in that is requires a physical cable pair per circuit. The signalling circuit uses the same cable pair as the talking path, and filters are not required to separate the signalling from the voice transmission. One wire of the pair is used for signalling and the other to compensate for differences in ground potential and partially for variations in battery voltages. At each end of the line a polar relay (Refer to Figure 6-22) with four equal windings is connected to the trunk conductors at the midpoints of a repeating coil. A balancing network consisting of resistance and capacitance is provided at each terminal between the P2 and P3 windings. The resistance of this network is adjusted to equal the conductor loop resistance plus 1220 ohms.

Both M leads are grounded and both DX relays are electrically biased to the non-operated position by the P2 and P3 windings from the negative potential of the voltage divider when the trunk is idle. There is no current flowing over either trunk conductor when there is no earth potential difference. When one end is off-hook, battery is placed on the M lead thus causing the distant DX relay to be operated to ground on its M lead. At the near end, current in the P2 and P3 windings is reversed tending to operate the polar relay but the signal current through the P1 winding more than offsets this effect and holds the relay non-operated. When both ends are off-hook, both M leads are connected to battery and each DX relay holds operated to ground on the voltage divider. As in the case of on-hook at both ends there is no current over either trunk conductor if no earth potential difference is assumed. However, when earth potential differences do exist they produce opposite and approximately equal effects on the P1 and P4 windings at each end of the trunk and so are neutralized.

DX signalling transmits nominal 10 or 20 pps dial pulsing with little signal distortion. No pulse repeating adjustments are required. A single DX signalling section is limited to a maximum loop resistance of 5000 ohms. This range can be doubled by using two sections in tandem.

DX signalling is expected to be used instead of loop signalling on long local and tandem trunks and instead of SX and CX on short intertoll trunks except where open wire or nonphysical circuits prevent its use. It can be operated without impairment through E type repeaters.

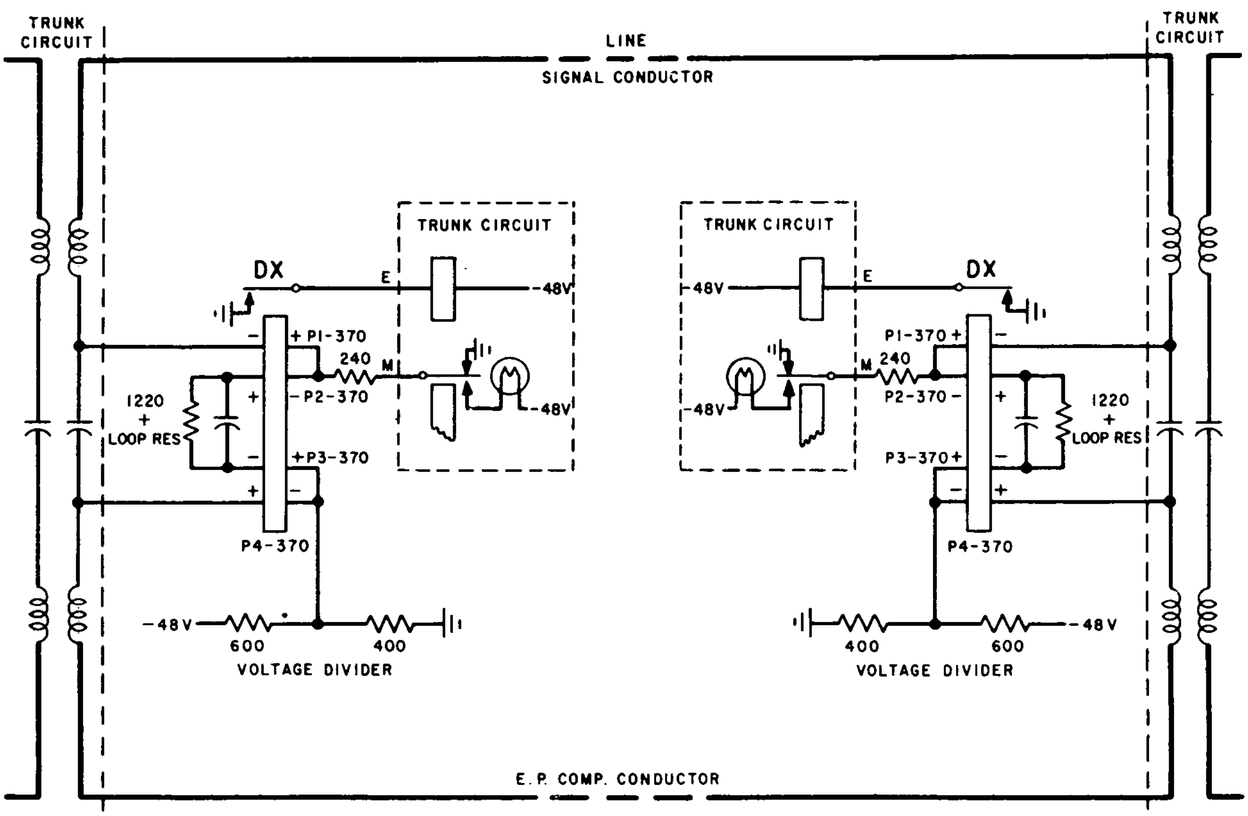


Figure 6-22. Duplex (DX) Signalling Circuit

Voice Frequency Systems

The term "voice frequency" signalling was originally applied to the 1000 cycle ringdown system, for it used a signalling frequency within the voice frequency range. Since modern signalling and supervision systems must also be capable of passing pulsing information for intertoll dialing purposes the designation, "voice frequency system", is now restricted to the more modern systems discussed below.

Voice Frequency Telegraph System (VFT) - It was noted under the discussion of Composite (CX) signalling systems that they were derived from full duplex telegraph systems. There are carrier systems which will derive up to 18 full duplex telegraph channels from any four-wire type speech channel of normal band width. The carrier telegraph system, of course, precludes the simultaneous use of the same channel for speech purposes.

Some of the speech carrier systems such as the Type C, H, J, K, and L which do not have dial signalling and supervision features built-in as an integral part of their terminal equipment may have signalling channels supplied by V.F. telegraph systems. The addition of an auxiliary pulse link at the V.F. telegraph terminals will derive the necessary E and M leads to which the trunk circuits may be connected.

The use of V.F. carrier telegraph channels for signalling and supervision channels is somewhat expensive but in some cases their use may be justified; particularly if actual telegraph circuit requirements also exist along the same route.

Single Frequency System (SFS) - With the advent of nationwide intertoll dialing, it was necessary to develop a new and cheaper signalling system which could be directly associated with speech channel terminal equipment and which would avoid the use of separate channels for signalling, such as V.F. carrier telegraph channels.

The first system developed used a 1600 cycle frequency applied to each one way transmission path of four-wire type speech channels. This frequency was chosen so that this system could also be used with Type EB* narrow band channel splitting carrier systems which had an upper speech frequency limit of about 1750 cycles. When this system is applied to two-wire V.F. facilities it is necessary that a repeater be used at the circuit terminals to derive a four-wire point to which the system can be applied. It is also necessary that a second frequency be used, so that signal and pulsing transmissions in opposite directions on the two-wire line will not interfere with each other. This second frequency is 2000 cycles, so the arrangement is known as the 1600/2000 cycle system.

*Type EB systems were a World War II expedient to divide normal band width four-wire speech channels into two lower quality speech channels.

A later and cheaper version of the single frequency system uses 2600 cycles for four-wire type facilities and 2400 cycles as the second frequency if it is applied to two-wire V.F. circuits. This system is, therefore, designated as the 2400/2600 cycle system.

The presence or absence of signalling tone in the two directions provides all of the signalling, pulsing and supervision features required for inter-toll dialing. Absence of such tone provides the necessary supervision features during the conversation period. However, the signalling tones are present in normal speech, and rather elaborate guarding arrangements are necessary to prevent false operation of the signalling equipment during the conversation period.

Built-In Signalling System - The Type N, O, and ON carrier systems have an upper speech band limit of about 3100 cycles, in a 4000 cycle channel space. This made it possible to build a signalling system into each carrier channel terminal unit arranged to operate on a 3700 cycle tone. Since the signalling tone of the N, O and ON carrier systems is outside the speech band, the elaborate guard arrangements to avoid interference from speech can be omitted with a consequent saving in the cost.

Multi-Frequency Key Pulsing System (MFKP) - The direct-current and single-frequency signalling and supervision systems that have been discussed thus far are arranged to transmit pulsing information in the same manner as pulses are generated by the telephone station or operator's dial, i.e., five sequential pulses represent the digit 5, ten sequential pulses represent the digit "0", etc. The time required to transmit dial pulses constitutes a considerable portion of the circuit holding time required for transmissions with consequent loss of efficiency in the use of expensive outside plant, terminal equipment and switching equipment.

To reduce the holding time, a system was devised whereby the telephone station number and routing digits could be individually and completely identified by very short simultaneous spurts of combinations of two tones. This system is known as the Multi-Frequency Key Pulsing System. Maximum speed of the multi-frequency key pulsing system is about 7 complete digits per second (i.e., a complete 2L-5N station number) as compared with only 10 dial pulses per second (i.e., the digit "0" only).

For operator dialing a 12 button key set is used (10 for number digits). Due to human limitations, maximum speed of the MFKP equipment is not attained by operators. However, the maximum speed can be attained by the senders of a mechanical switching system when spilling pulsing information forward in building up a connection.

Because of the cost, MFKP equipment is not provided individually for each trunk. It is connected automatically only as and when needed. Therefore, two codes in addition to the 10 digits are required. One, designated "K.P.", prepares the receiving equipment at the distant office to accept the digit information which will follow. The other, designated ST (Start), advises the distant equipment that it has received complete digit information and it may start delivering it to other equipment and then release itself from the connection.

Six single frequency tones spaced at 200 cycle intervals from 700 cps, to 1700 cps, both inclusive, are used for this system. Various paired combinations of two of these tones identify the individual number digits and the "KP" and "ST" indications. It should be noted that the MFKP system is used for pulsing information only and is not a complete signalling and supervision system. Accordingly, it must be supplemented by the use of one of the other systems, such as the DC or SFS types for the remaining signalling and supervision features.

CHAPTER 7

TRANSMISSION DESIGN

Every telephone customer wants to enjoy an easy exchange of information and to recognize a familiar voice. A circuit that is to satify these desires must meet certain transmission requirements. The speech sounds delivered to the listener's ear must be of adequate volume and band width. Echo, crosstalk, noise, and distortion must be limited. The circuit must not be allowed to sing. These requirements and the manner in which circuits are designed to satisfy them are discussed in this Chapter.

Transmission Limitations

Volume - The primary problem in transmission design is insuring the delivery of an adequate volume from the listener's receiver, so that he can hear clearly and easily. We can get more volume to the listener only by reducing the transmission losses between the talker and the listener.

Within the past few years, a rather exhaustive series of observations was made at the Laboratories in which various over-all effective transmission losses were presented to a large number of people. They were asked to rate them as "good", "fair", "poor", "unsatisfactory", and "can't understand". More than 1000 people participated in these tests. The results are shown in Figure 7-1.

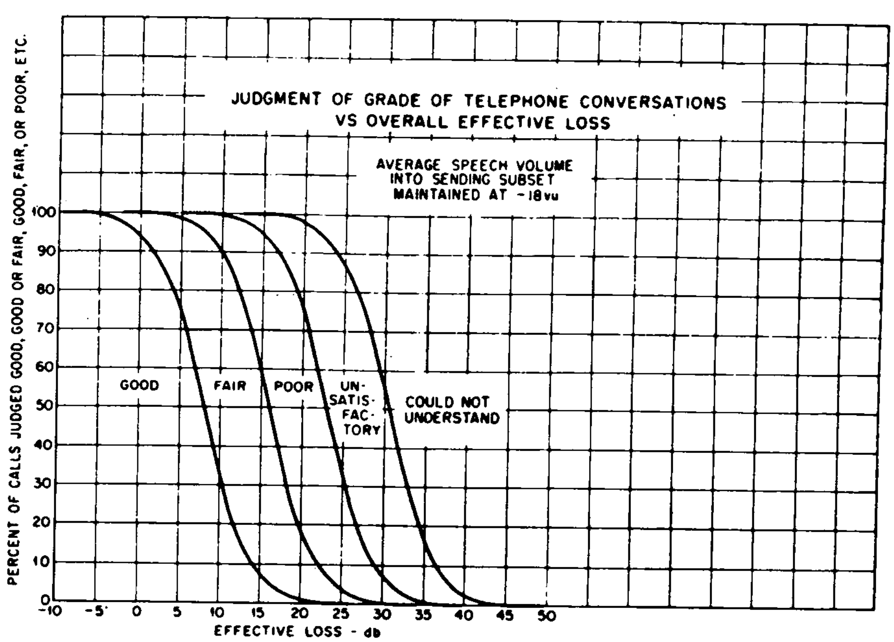


Figure 7-1.

From the results of these tests we can draw three conclusions:

a. There is a 20 to 25 db range between the most critical and the least critical observers.

b. If we are going to establish a grade of transmission which would be considered good by practically everybody, the losses will have to be very low indeed.

c. Transmission was rated poor by people when they were able to understand perfectly well what was said. Accordingly, it is apparent at the present time that people expect very low losses between the talkers and the listeners.

Table 7-1 shows the progress that has been made during the past 25 years in reducing the over-all losses between talkers and listeners on intertoll connections, and the objective which it is hoped may be attained during the next 5 to 10 years.

OVER-ALL INTERTOLL EFFECTIVE LOSSES - DB
(Subscriber to Subscriber)

	Average	99 + %
25 YEARS AGO	16	30 or LESS
10 YEARS AGO	10	25 or LESS
NOW	6	20 or LESS
OBJECTIVE	−4	6 or LESS

Table 7-1.

Frequency Band Width - Bare information can be conveyed by a reasonably narrow band of frequencies, but the average telephone user has shown that he desires more. He wants the talker's voice to sound as it would if they were conversing face to face. This requires a materially wider band.

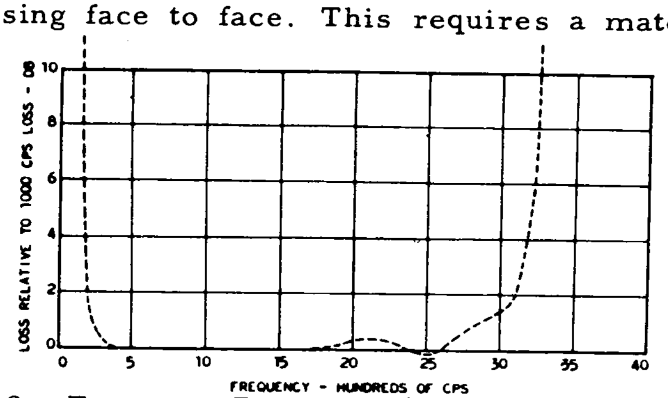


Figure 7-2. Frequency Response of Type N1 Carrier Channel.

At the present state of the art, a band width of about 250 to 3000 cycles per second is considered adequate to convey information with a high degree of naturalness. Most modern intertoll facilities meet or exceed this band width. Figure 7-2 shows the frequency response characteristic of a modern Type N1 carrier system having a pass band of this range. If the band width is less than this amount it is generally necessary to reduce the circuit net loss (i.e. provide increased volume) to overcome the Distortion Transmission Impairment and attain comparable transmission results (see Chapter 4).

Echo - Echo is just what its name implies. It is the repetition of sounds out of a receiver which result from currents bouncing back from electrical obstacles in a telephone circuit - just as acoustical echo is the effect of sounds bouncing back from physical obstacles. In both the acoustical and electrical cases, the obstacle is a mismatch in the impedances encountered by the signal.

Two factors determine the degree of customer annoyance due to echo:

a. Its loudness.

b. How long it is delayed.

The talker is usually more affected by echo than the listener.

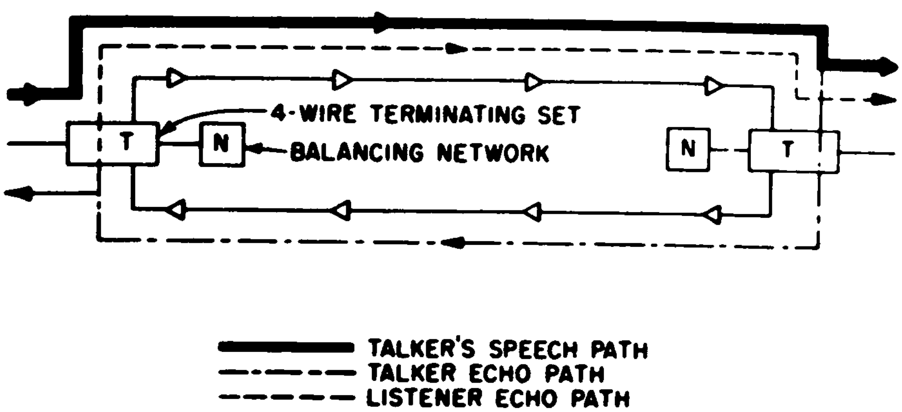


Figure 7-3. Echo Paths in a Four-Wire Circuit.

Let's consider what determines loudness and delay. They are illustrated in Figure 7-3. For simplicity, a four-wire circuit is shown. In such a circuit there is only one obstacle which causes echo. It is the impedance mismatch between the network and the circuit facilities which may be connected at the far (right-hand) end. The loudness of the echo, in this case, is determined by three factors:

a. The circuit loss from the talker to the far end. That is, the loss at which the circuit is operating in that direction.

b. The loss across the four-wire terminating set due to the impedance mismatch between the network and the terminal facilities. The greater the mismatch the less the loss, and vice versa. This is called the "terminal return loss".

c. The circuit loss from the far end back to the talker. This is the loss at which the circuit is operating in that direction.

The delay of the echo, in this case, is the time it takes a talker's speech to go to the far end of the circuit and back again; quantitatively, it is twice the circuit length divided by the velocity of propagation.

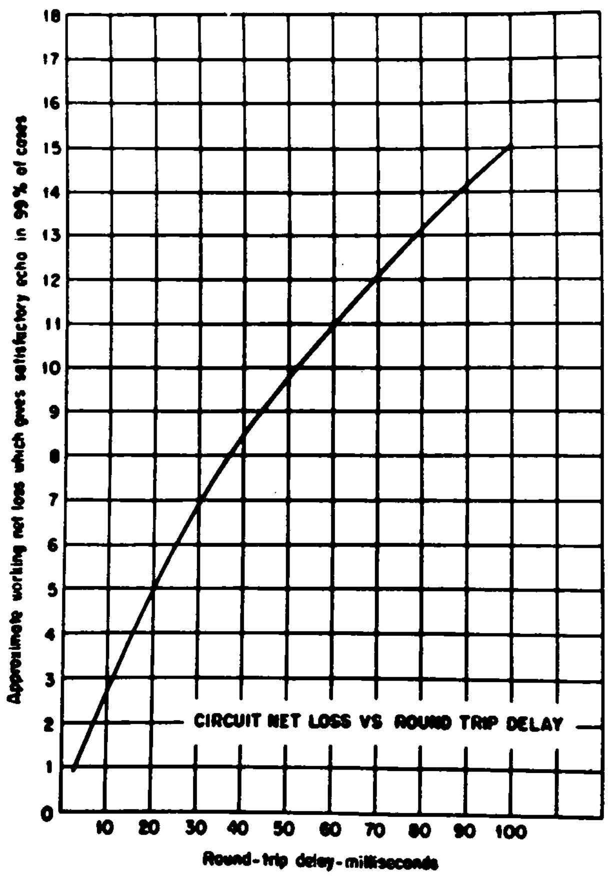


Figure 7-4. Results of Talker Echo Tolerance Tests.

People will tolerate a much louder echo if the delay is short than if it is long. If the delay is short enough the echo sounds like more side-tone. Unless it is unusually loud, the talker hardly knows that it is present. But when the delay is long, the echo volume must be much lower (i.e., the circuit loss must be greater) if the talker is to be kept happy. This is illustrated by Figure 7-4.

The velocity of propagation of loaded voice frequency cable circuits ranges from about 10,000 to 20,000 miles per second, whereas carrier system circuits have a speed of about 100,000 miles per second or more. Accordingly, carrier system circuits are about 5 to 10 times better from an echo standpoint for circuits having the same losses.

Echo on two-wire repeatered circuits is a more complex problem, since it involves a multiplicity of paths having different amounts of circuit loss and different amounts of delay. This is illustrated by Figure 7-5.

Methods are available for combining the various path losses and delays of such circuits to obtain a resultant loss and delay which can be checked against Figure 7-4 to determine if the circuit is satisfactory from an echo standpoint.

Aside from echo suppressors (which should be used very sparingly) the methods that can be used to control echo are as follows:

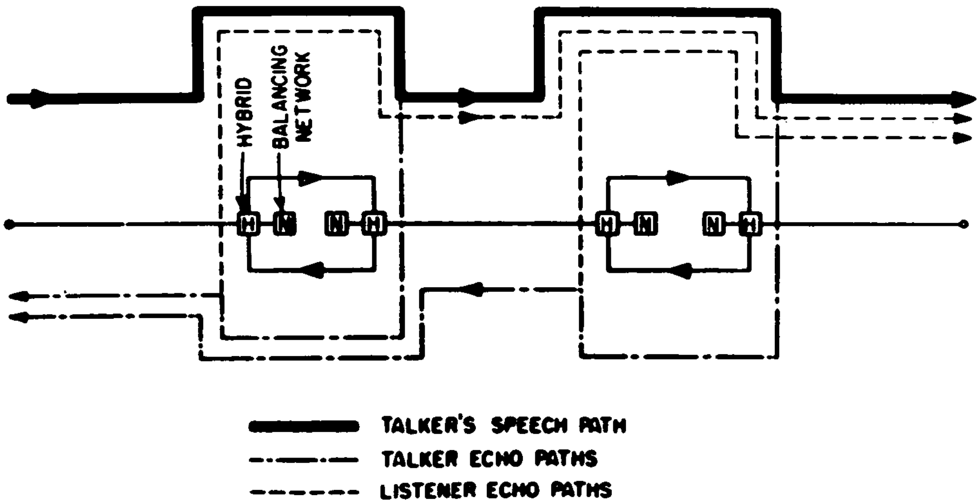


Figure 7-5. Echo Paths in Two-Wire Repeatered Circuit.

a. Reduce impedance mismatches (i.e. improve circuit return losses).

b. Control the circuit net loss.

c. Choose facilities having a suitable velocity of propagation.

Singing - Singing, i.e. sustained oscillations or "repeater how", is another factor in circuit design. Circuits which are "singing" are unusable.

Singing might be thought of as echo which is completely out of control. This can occur at the frequency at which the circuit is resonant. Under such conditions, the circuit losses at the singing frequency are so small that oscillation will continue even after the impulse that started it has ceased to exist.

In the older types of intertoll plant, which were operated largely on a two-wire basis with repeaters, singing was generally the controlling factor in determining the lowest permissible circuit loss. With the present day intertoll plant being operated largely on a four-wire carrier basis, singing has almost ceased to be a controlling factor in intertoll circuit design. It may, however, be a controlling factor in the design of the repeatered exchange trunks to which intertoll facilities may be switched as the terminal links in establishing the connection between two subscribers.

Crosstalk - Crosstalk is defined as extraneous electrical signals which are induced into an operating communications channel from a similar paralleling channel. This may be due to:

a. Leakage through common electrostatic or electromagnetic coupling paths between the channels. (Direct and interaction crosstalk.)

b. Inter-modulation in a non-linear amplifier used in common by several channels of a carrier system. (Inter-modulation crosstalk.)

c. Crosstalk currents reaching the disturbed channel which, though out of band, are brought in-band by a modulator in the disturbed channel. (Image crosstalk.)

Induced crosstalk signals tend to travel in both directions along the disturbed circuit from the point where they are induced. Crosstalk that travels toward the talker on the disturbed circuit is designated as near end crosstalk and that which travels toward the listener is designated as far end crosstalk.

Near end crosstalk may be a limiting transmission factor for two-wire circuits and far end crosstalk may be a limiting factor for four-wire circuits.

Crosstalk can be controlled by the following methods:

a. Proper design of the transmission system plant.

b. Proper maintenance of the transmission system plant.

c. Control of the disturbed circuit losses so that the crosstalk currents may be attenuated to tolerable values before they reach the talker or the listener.

Noise - Noise may be defined as unintelligible sounds in a transmission system which tend to mask the desired speech transmission. Noise can be subdivided into two general classes:

a. Internal noise.

b. External noise.

Internal noise is generated within the transmission system of interest and consists generally of the following components:

a. Thermal noise due to random movement of electrons in various components of the transmission system. Such noise increases with increasing temperatures of the operating components.

b. Dial contact noise caused by minute electrical arcs across dirty or loose contacts.

c. Noise from generators used for charging central office batteries.

d. Transmitter frying (now largely eliminated).

In general, transmission systems are so designed and maintained that internal noise is not a limiting factor in determining intertoll circuit losses.

External noise is induced into the transmission system from external sources and consists of the following general types:

a. Ambient (or room) noise at the talker and listener locations.

b. Impulse noise from the operation of dial office or telegraph equipment.

c. Atmospheric noise.

d. Crosstalk babble from a multiplicity of parallel disturbing circuits.

e. Induction from radio systems.

f. Power line induction.

A general approach to noise arising from external sources is to find ways to eliminate it rather than to adjust circuit losses to compensate for it.

Distortion - There are no electrical transmission systems which permit the perfect reproduction of intelligence. In general, it can be said that the greater the degree of perfection attained, the more costly the system will be. The three basic factors causing distortions are:

a. Phase distortion (delay distortion) due to differences in the speed of propagation for various frequencies in the transmitted band.

b. Attenuation distortion due to differences in circuit losses for various frequencies in the transmitted band.

c. Non-linear distortion due to the presence of non-linear impedances in the system.

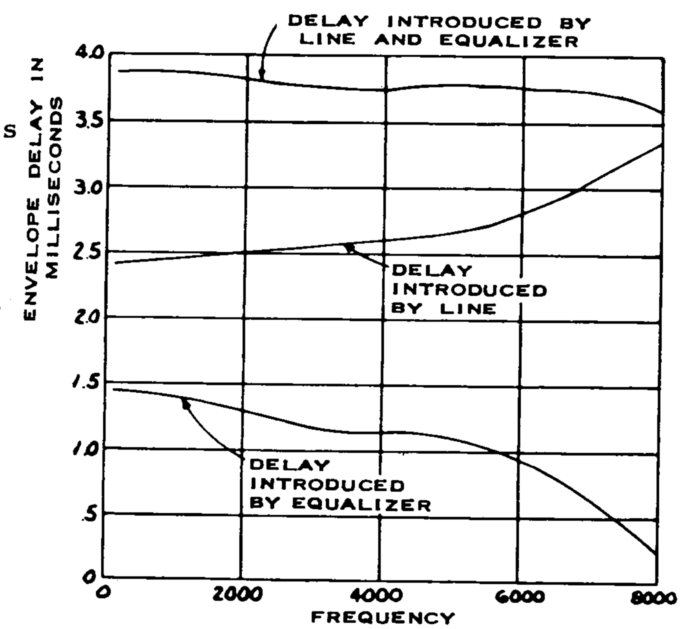


Figure 7-6. Principle of Delay, or Phase Equalization.

The human ear is relatively insensitive to phase distortion. However, when necessary, this type of distortion can be controlled by the use of phase equalizers as illustrated by Figure 7-6. Phase distortion is not generally a factor in establishing intertoll circuit losses.

Attenuation distortion tends to impair the intelligibility of speech transmission. Such distortion may also be controlled by the use of equalizers as is illustrated by Figure 7-7. Another method used in some carrier systems is frequency inversion and frogging. In general, unless the speech band width is narrowed between 250 and 3000 cycles per second, as mentioned previously, attenuation distortion is not considered to be a limiting factor in establishing intertoll circuit losses.

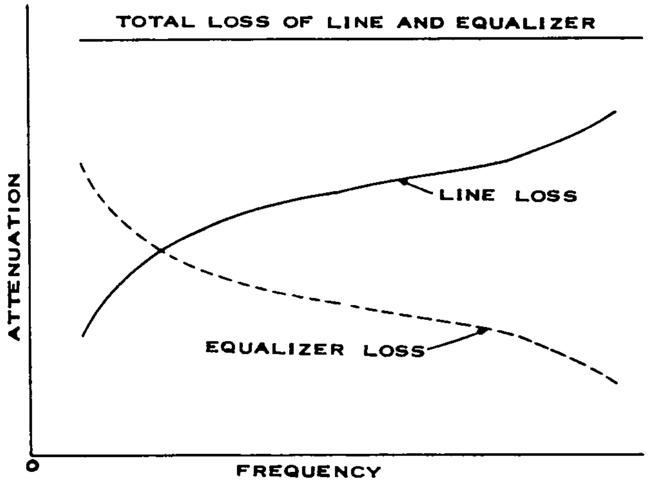


Figure 7-7. Principle of Attenuation Equalizer.

Non-linear distortion may arise when elements are present in the circuit in which the relation between voltage and current is not substantially linear. Overloaded vacuum tubes, saturated core transformers, and varistors may all give rise to this form of distortion. The effect is to generate additional frequencies in the transmission system which were not present in the original signal. If these new frequencies fall in the speech band correction is usually impracticable. Prevention, by proper design and maintenance of equipment, is therefore essential.

The New Look in Transmission Design

Over the years, a number of transmission "standards" have been adopted. They all established a limiting transmission loss between any two subscribers, and provided for the distribution of this over-all loss among the several types of circuits making up a connection. The only variable under the control of the transmission engineer was loss, and every reduction in loss was purchased with heavy expenditures for copper. Each central office was assigned a maximum local loop loss which was determined by a "loop and trunk study". These studies were made for each exchange, to determine what division of loss between loops and trunks would give the lowest over-all cost. Naturally, this balance was influenced heavily by the trunking plan and the local office's relation to the national switching network.

The advent of improved station instruments and relatively inexpensive repeaters and carriers permitted a new look in transmission design. For they gave the transmission engineer a new tool - cheap gain.

Today, loops in all exchanges are designed to the same objectives without regard to the trunking plan. And all trunks for interconnecting these loops are now held to the lowest loss practicable at the present stage of the telephone art.

Let's explore the new look in transmission design in a little more detail.

Loop design used to be pretty much a matter of transmission. We put in heavy enough copper to make the loop talk-up to the limit established by the loop and trunk study. Then, when we checked the loop resistance against the office range, there was usually some margin. Now the practice is to put in just enough copper to meet the supervisory limit. For the greater loss of fine gauge plant can be overcome by the judicious assignment of higher efficiency station sets and the more liberal use of loop loading. Loops designed on this basis have a limiting transmission of about −2 db effective — as compared with the old limits which ran in the order of +1 to −6 db effective, depending upon the results of the loop and trunk study for the particular exchange. This slight relaxation in limiting transmission of some exchanges has been offset by the new look in trunk losses. The end result has been a slight improvement in over-all limiting transmission. But of greater significance is the fact that the new approach has made a material improvement in average transmission, which benefits the majority of users. And it has been done with cheaper outside plant. The only real problem has been keeping trunk loss reduction in step with changes in loop loss during this period of transition.

Figure 7-8 shows what has happened to trunk costs in the last few years.

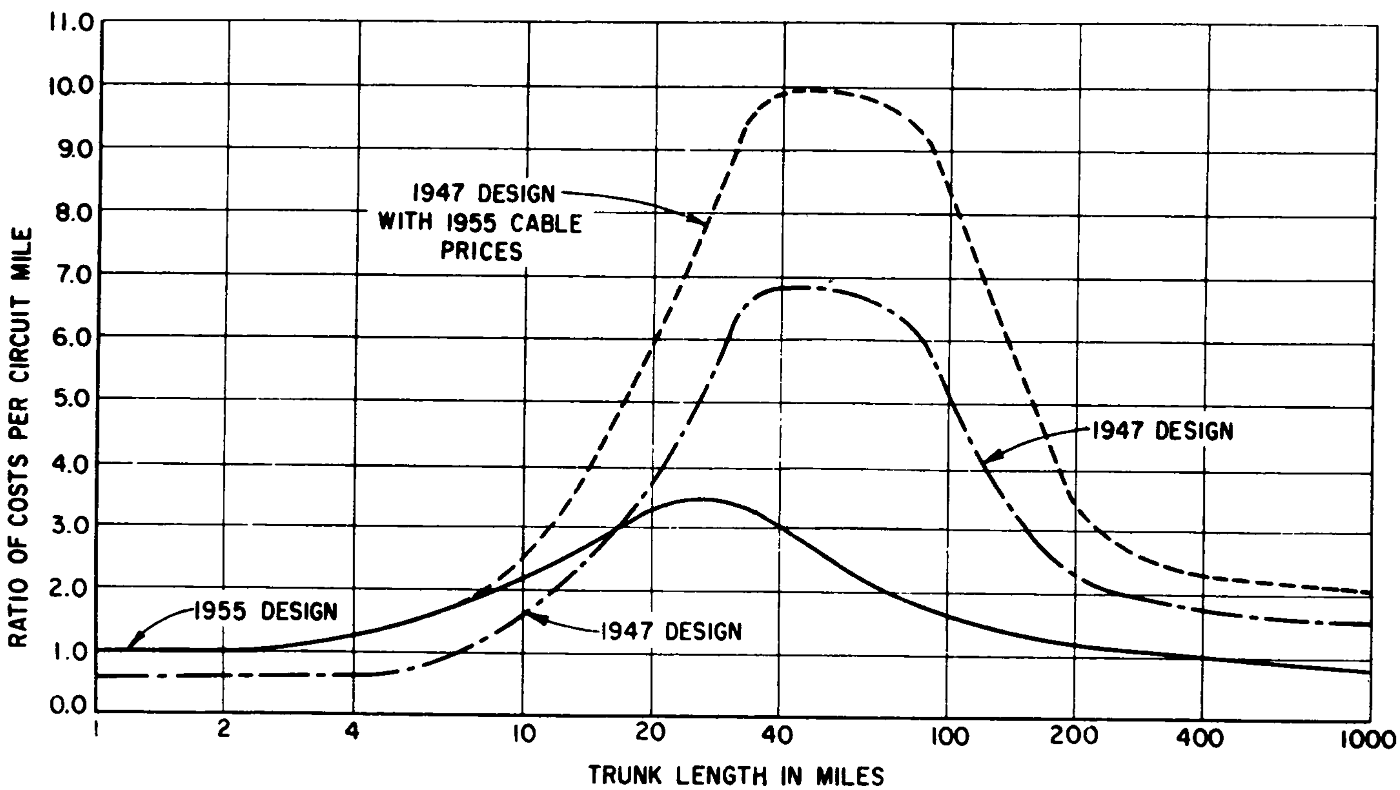


Figure 7-8. Approximate Relative Costs of Trunks - 1947 vs 1955.

The E-Type repeater is doing much the same thing for short-haul trunks that the more efficient station instrument has done for local loops. We can usually get a lower loss circuit using small size copper, with inexpensive repeaters and light loading, than we used to get with heavy copper and heavy loading. And it is a better circuit and a cheaper one. There are still some soft spots in the short-haul trunk business. We can't do all the things that we would like to do — at least not as cheaply as we would like to do them. But the E23 has been a big help, and we have every expectation that other instrumentalities will be coming along to help further reductions in costs and losses.

The demand for large numbers of circuits and the economies of electronic gear have made carrier king in the medium and long-haul trunk field. Beyond about 20 to 30 miles, there is usually no relation between the loss of a trunk and its cost. We put in carrier, either on wire or on radio, because it is the cheapest way to provide circuits. It doesn't cost us anything to decrease the loss of a carrier channel — we just twist the knob of a potentiometer with a screwdriver. The trouble is that we must make improvements in our plant (particularly in toll offices) before we can use the free gain that is lying idle in many of our carrier systems. This is part of the "Via Net Loss" concept which we will look into a little later in this Chapter.

One more thought before we take up some of the principles of transmission design: In practice, particularly in large metropolitan areas, trunks cannot always be fitted into the somewhat academic classifications suggested in Chapter 6. This presents no great problem in transmission design — not as long as we keep our eye on the objective. Trunks — all trunks — are to be made as short as possible, while loops stand on their own feet.

Subscriber Loop Design

The optimum design of the local loop plant is of considerable importance. Two loops are a part of every telephone connection so their electrical performance has a strong influence on the transmission quality of the service we provide. On the other hand, loops account for a substantial percentage of the plant investment, and economical design is essential.

Introduction of the 500-type telephone set has permitted extension of the subscriber loop range and simplification of loop plant design methods. With the improved transmission performance of the new set, the loss of the loop is no longer the controlling limitation. Now the limitation is the conductor resistance range determined by the supervision and pulsing capabilities of the central office equipment. So the current subscriber loop plant design method is called "resistance design".

Resistance design is applied by use of the following simple guides:

a. Select the most economical (smallest) gauge, or combination of consecutive gauges, permitted by the conductor resistance range of the central office.

b. Provide loading on all loops longer than 18 kilofeet. From the standpoint of transmission and economic design, the H88 loading system is usually the most attractive.

c. Administer the installation of station instruments so as to exploit their transmission capabilities most effectively, within the limitations of the existing supply situation. This procedure is called "zoning". At present, the older instrument types are restricted to those loops having an effective transmission equivalent of 0 db or better (475 to 1150 ohms depending upon cable gauge). From this point out to 1500 ohms, 500 type sets are installed. Local battery sets are required on loops of higher resistance.

d. Limit cable bridge tap to 6000 feet, and restrict the total length of drop wire in a loop to 500 feet.

Very long suburban loops present a special problem. Meeting the office resistance range at the end station may require considerable coarse gauge cable. An economic balance must be struck between a cheaper high resistance loop (with less copper) and the expense of extending the office range with long line equipment.

Since the choice of cable gauge depends only on conductor resistance, detailed knowledge of the transmission art is not required, and loop design is generally performed by the field engineers in the Plant Department. In spite of its simplicity, resistance design of the loop plant insures good transmission, as long as trunk losses are made as low as practicable.

Interlocal Trunk Design

Trunk losses are usually assumed to be made up of the following components:

(1) Wire, or facility loss.
(2) Terminal junction losses.
(3) Intermediate junction losses.
(4) Losses due to loading coil spacing irregularities.
(5) Office losses at intermediate switching points.
(6) Losses due to any other intermediate or auxiliary equipment.
(7) Repeater gains (negative losses).

Since originating and terminating central office losses are usually small and uniform in size, they are neglected in most studies.

Junction and loading irregularity losses can be disregarded provided they are small. If they are not small, measures should be taken to reduce or eliminate them. The other miscellaneous losses are usually small and can be disregarded. So, trunk loss can be taken as facility loss, minus the gain that is inserted if repeaters are used.

The design objective is to make all trunk losses as low as practicable and independent of loop losses. With this approach, and taking costs and new instrumentalities into account, it appears that a practical and economical design objective for the next five to ten years is a 4 to 6 db maximum loss for interlocal trunks. However, for the next couple of years or so, a db or two above this maximum loss is acceptable for non-repeatered trunks, where the cost of improvement is excessive. Where repeaters are used, the loss should be reduced to the minimum value that can be obtained while still maintaining circuit stability.

In metropolitan areas, over-all economy can frequently be secured by routing all or a portion of the interlocal calls through one or more intermediate switching points. The design of these tandem and intertandem trunks should be such that the sum of the losses of the two or more trunks in any possible connection between local offices will not exceed the 4 to 6 db objective. A further limitation is also imposed; none of the possible connections between two stations in the exchange area should have a transmission contrast of over 5 db.

The signalling on virtually all interlocal trunks is still on a DC basis. Trunk range varies between about 600 and 3000 ohms, depending upon the type of central office.

Knowing the transmission requirements and the maximum resistance allowable, the problem is to meet these objectives in the most economical manner. Transmission is controlled by the choice of gauge, type of loading, whether or not the trunk is repeatered, and if so, the repeater type and locations. The resistance limitation must be satisfied by gauge selection, or the limitation modified by the use of long trunk equipment or signalling repeaters.

The Intertoll Trunk Design Problem

The design of intertoll trunks is intimately related to the Nationwide Dialing Plan. The Plan is discussed in detail in the literature and will not be described here. However, for reference, Figure 7-9 shows the relation of the several classes of offices in an all final route connection.

The Plan provides for two terminal links and up to seven intertoll circuits connected in tandem on calls within the U.S. As a result of alternate routing, different numbers and makeups of intertoll circuits may be encountered on successive calls between the same two telephones. Transmissionwise, this means that the loss of each link which may be used in a connection must be low, in order to provide adequate transmission on all calls and to avoid large differences in transmission on successive calls between the same two places.

The ideal would be to operate all circuits at zero loss, since this would make the transmission independent of the number of circuits used in a connection. However, the distances in the U.S. and Canada are so great that even the best types of transmission facilities must be operated at some loss to insure suitable transmission characteristics.

The minimum loss at which a trunk will provide satisfactory service is usually limited by echo, singing, noise and crosstalk. At one time it was the practice to overcome these objectionable effects simply by designing or adjusting trunks so that they would have a higher loss. This technique is contrary to the requirements of the present switching plan, and we have had to take a new look at intertoll trunk design.

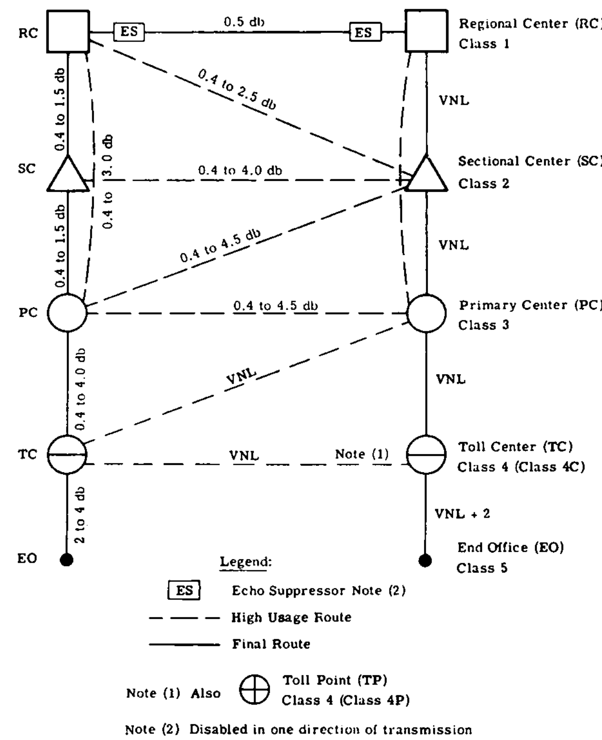


Figure 7-9. Nationwide Dialing Plan.

We can provide a better grade of transmission if we control noise and crosstalk in the design of individual transmission systems and the layout and construction of associated plant — not by running up circuit losses. In other words, the preferable approach is to get at the basic cause of noise and crosstalk and not to cure only the symptoms.

Generally speaking, circuit losses that satisfactorily control echo will prevent singing. (Of course, impedance irregularities must be controlled in 2-wire lines to permit precision balancing of line hybrid nets.)

From a practical standpoint then, echo is usually the controlling factor in intertoll trunk design today.

We have seen that the amount of echo that a customer will tolerate is governed by two things: loudness and delay. Echo delay is determined by the propagation velocity, or speed, of the circuit and the circuit length. For a facility of given length, the faster the circuit, the less the delay. This truism suggests the use of carrier, but the bulk of our circuits of any appreciable length are already on carrier for economic reasons. And we can't make our carrier much faster, because they have speeds which approach that of light, which is the theoretical maximum. This leaves echo loudness as the variable under our control.

For a given talker volume, echo loudness is fixed by the losses in the echo path. These losses are: the loss of the circuit out to the far-end, the loss across the 4-wire terminating set at the far-end, and the loss from the far-end back to the talker. Since circuits are operated at the same loss in both directions, we can say that the echo loss is twice the loss of the circuit plus the return loss at the far-end. Circuit loss is the factor we are attempting to determine, so let's look at the return loss half of this relation.

Four-wire switching points have an infinite return loss and present no echo problem, since no 4-wire terminating sets are required.

Two-wire intertoll switching points (Primary Centers and offices of higher rank) are a possible source of echo, for we must have 4-wire terminating sets to get our 4-wire carrier or repeatered facilities down to the 2-wire switching paths. The typical arrangement at this type of office is shown in Figure 7-11. Here, return loss is determined by the degree of match between the impedance of the compromise network (R-C) and the impedance presented to the drop side of the hybrid by the office. Studies have shown that with a return loss of 27 db, a 2-wire switching point ceases to be a significant contributor to echo. Large offices are apt to have a somewhat poorer balance, but their return loss can be increased to 27 db without great difficulty by a process known as "office balancing".

At offices functioning as Toll Centers, the compromise network of the equipment terminating the intertoll trunk is matched against the impedance presented by the terminal link, end office, local loop, and listener's station set in tandem. Experience has shown that the terminal return loss under these conditions will average about 11 db. Maintaining even this relatively low balance requires "switching pads" (or their equivalent) between the intermediate and terminal link and "impedance compensation" on the terminal links under some conditions. So we see that the terminal return loss is controlling and return loss at intertoll switches can be disregarded.

Now we are in a position to state the design requirements for the loss of an intertoll trunk. With the round-trip echo delay established by the speed and length of a circuit, we can write the following equation for circuit loss:

Round-trip circuit loss + Terminal return loss = Talker's echo tolerance,

or stated in another way,

One-way loss = 1/2 (Echo tolerance - Terminal return loss)

Several new terms have been introduced in the preceding discussion. One of them, "switching pads", may need clarification before we turn to the practical technique for applying the design criterion we have established.

Switching Pads

An intertoll trunk may be operated in either of two conditions:

a. In the "Via Condition" the trunk is an intermediate link in a switched connection and both ends are extended by other intertoll trunks.

b. In the "Terminal Condition", the trunk is terminated in a telephone set at one or both ends through local plant.

When in the via condition, a trunk is either switched on a 4-wire basis or on a 2-wire basis in an office where care has been taken to insure a good impedance termination. In either case, the possible echo return path in the switching office has been effectively eliminated. This is not the case when a trunk is in the terminal condition.

Experience has shown that a trunk must have a higher loss in the terminal condition than when working in the via condition. For practical operation of the intertoll network, we must be able to use the same trunk for both terminal and via service. This dual operation is made possible by introducing a loss at the end of an intertoll circuit when in the terminal condition. Until recently, this loss was provided by a pad in the intertoll trunk equipment. The equipment was arranged so that the pad remained in the connection when the intertoll trunk was switched to a toll connecting trunk. However, the pad was automatically removed when the intertoll trunk was switched to another intertoll trunk, since it served no useful purpose. These pads are known as "switching pads" or simply "S" pads.

An S pad benefits transmission in several ways:

a. It prevents amplifier overloading due to excessive talker volume from short loops.

b. It provides a measure of control over crosstalk from excessive talker volume on short loops.

c. It improves the return loss by twice the loss of the S pad, for echo currents must pass through the pad twice while speech currents pass through the pad only once.

Via Net Loss

Before we stopped to discuss S pads, we defined the condition which established the minimum practicable loss in an intertoll trunk. This minimum loss is known as Via Net Loss.

Defined in broad terms, Via Net Loss is the minimum loss in db at which a circuit can be operated in the via condition without objectionable echo, **singing**, noise or crosstalk.

For practical design purposes, a procedure has been developed for determining VNL (Via Net Loss) for each type of facility, as a function of the length of the link. The procedure makes use of a set of factors called Via Net Loss Factors (VNLF). The appropriate VNLF, multiplied by the circuit length, gives the VNL at which each circuit can be operated, regardless of the number of links in the connection.

At the beginning of this Chapter, Figure 7-4 was introduced to illustrate, in a general way, the relation between echo loudness and delay that would be tolerated by a telephone user. This same information is plotted as Curve X in Figure 7-10. Now that we have explored the echo problem more fully, we can make a more sophisticated interpretation of this curve. For each value of round-trip delay, the loss indicated by the curve is an evaluation of the equation on page 128.

One-way loss = 1/2 (Echo tolerance - Terminal return loss)

In making these evaluations, statistical techniques were used to recognize the the following factors, assuming the connection to have a single intermediate link:

a. The manner in which echo tolerance varies among a large number of talkers.

b. The manner in which a large number of measurements of actual terminal return loss varied from the average of 11 db.

c. The manner in which circuit losses have been found to depart from their assigned values.

And, finally, the equation was so weighted, that considering all variables, the probability of a talker being slightly disturbed by echo is only one chance in a hundred.

Now let's see how Curve X can be used in determining Via Net Loss Factors. Suppose we start by considering the loss necessary in a single link circuit having zero round-trip delay. Since our circuit has a single intermediate link, this link will be in the terminal condition and will have an S pad at each end. Consideration of noise and crosstalk, singing and echo has indicated that in the present state of the telephone art an S pad of 2 db is the best value of switchable loss. So our circuit will have a loss of at least 4 db — the loss of a 2 db S pad at each end of the link. However, our intermediate link must be capable of operating in tandem with other links. Statistical studies indicate that an additional 0.4 db per link must be allowed if links are to be operated in tandem, since there is an increased probability that the over-all loss will deviate from the assigned value. This 0.4 db added to the 4 db for two S pads makes the minimum loss 4.4 db for a circuit with a single link and zero delay.

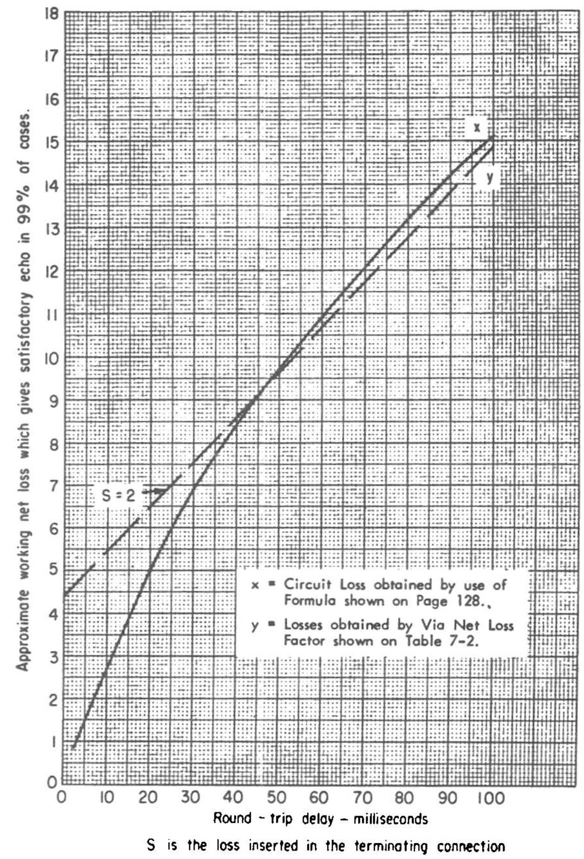


Figure 7-10. Approximate Relationship Between Round-Trip Delay and Permissible Working One-Way Loss For an Intertoll Trunk From Echo Standpoint for 4-Wire Circuits and 4-Wire Switching.

We have established the minimum practicable loss for the shortest possible circuit. Now let us consider the longest circuit that we may have to operate at Via Net Loss.

In the discussion of Transmission Systems, mention was made of the Echo Suppressor. You will recall that this is a voice operated device which eliminates talker echo. Experience has shown that satisfactory operation cannot be expected on connections with more than two Echo Suppressors in tandem (because of clipping and lockout in a high percentage of cases). Under the present view of the toll switching plan, it appears that circuits must be operated up to about 2500 miles without Echo Suppressors if the possible number of Echo Suppressors is to be limited to two. A 2500-mile carrier circuit will have a round-trip delay of about 45 milliseconds. This is the upper limit for VNL operation that we are seeking. Longer circuits can be operated at a loss independent of echo restrictions by inserting an Echo Suppressor. By designing all circuits with less than 45 milliseconds delay so that Echo Suppressors are not required, the switching plan will permit us to connect any two telephones in the United States without having more than two Echo Suppressors in tandem. Having determined the range of round-trip delay over which circuit loss must be dependent upon echo limitations, we can turn to the development of Via Net Loss Factors.

Referring again to Figure 7-10, and starting at the 4.4 db point on the 0 delay axis, a line (designated Line Y) can be drawn through the 45 millisecond delay point of Curve X. It will be seen that the slope of Line Y is the one way net loss in db per millisecond round-trip delay; and that the one way net loss corresponding to any point on Line Y is equal to 4.4 db (or 2S + 0.4 db) plus 0.1 db multiplied by the number of milliseconds round-trip delay.

With the velocity of propagation known for the various types of facilities employed, the slope of Line Y can be evaluated in terms of db per mile, a much more workable form. This is done by dividing 2 times the slope of Line Y by the velocity of propagation. (The factor 2 enters into the transformation since the db in the slope is one way while the delay is round trip.) The resultant db per mile figure is called the Via Net Loss Factor (VNLF).

Example: Intertoll trunks on K carrier have a velocity of propagation of 105,000 miles per second or 105 miles per millisecond.

$$\text{The VNLF is then } \frac{2 \times 0.1 \text{ db/ms}}{105 \text{ miles/ms}} = 0.0019 \text{ db per mile.}$$

To determine the lowest loss at which an intertoll trunk can be operated satisfactorily from an echo standpoint, it is only necessary to multiply the VNLF of the facility by its length. Table 7-2 gives the via net loss factors of the more commonly used facilities in the telephone plant.

Via Net Loss Factors for Typical Telephone Facilities

Facility	VNLF (db per mile)	
	2-Wire Facility	4-Wire Facility
19H 88-50 side	.03	.014
19H 88-50 phantom	.03	.014
19B 88-50 side	.04	-
19B 88-50 phantom	.04	-
19H 44-25 side	-	.010
19H 44-25 phantom	-	.010
Open wire, voice frequency	.01	-
Open wire carrier (all types)	-	.0017
Type K or N carrier	-	.0019
Type L carrier	-	.0015
Carrier circuits on radio	-	.0014
H88 on paired exchange type cables, any gauge	.04	-

Table 7-2

It will be noted from Figure 7-9 that echo suppressors are installed on each RC-RC circuit. On this basis, every connection involving an RC-RC circuit will contain one echo suppressor. It is hoped that by the use of only carrier facilities on the chain of final groups of circuits, echo suppressors can be avoided on the final route circuits other than RC-RC.

Office Balance

The via net loss factors shown in Table 7-2 assume that all interconnection of intertoll trunks at intermediate toll offices will encounter no appreciable echo paths at the switching centers. In 4-wire switching offices, such an echo path is automatically eliminated by retaining 4-wire operation through the switches. By careful engineering and maintenance, 2-wire switching systems can be made to give satisfactory transmission performance. The best transmission results are obtained if the switching system, the toll terminal equipment (carrier terminals or voice-frequency terminal repeaters), and the associated toll switchboards are in the same building.

On connections through an intermediate 2-wire switching point, echo can arise due to unbalance between the office equipment and wiring and the balancing network in the terminal repeater or 4-wire terminating sets. By using capacitors for balancing office cabling as outlined below, echo can be held to such small values as to cause little or no impairment on the switched connections.

In order to interconnect 2-wire circuits at random at switching points, a single type compromise network must balance any of the circuits in the office. It follows that the impedance of all the circuits terminating in the office must be equal to that of the network within reasonable limits of precision. A nominal toll office impedance of 600 ohms was selected some time ago (after due consideration of the relative series and shunt losses of office cable). Six hundred ohm impedance is currently used in the trunk circuits terminating at step-by-step, No. 5 crossbar, and No. 4 type toll crossbar offices. More recently, toll switching has been introduced at crossbar tandem offices which are designed to have office impedance to match the impedance of outgoing switching trunks. Since the present standard outgoing trunks are usually H-88 loaded cable, crossbar tandem office impedance for toll switching is considered to be 900 ohms. The circuit terminal impedances are designed to match the nominal impedance of the office. However, since supervisory signals are often transmitted over the talking path conductors, capacitors are required in certain locations to isolate parts of the signalling circuit. Consequently, the office impedance is assumed to be 600 or 900 ohms (depending on type of office) in series with a 2 mf capacitor, and circuit terminal impedances are so designed.

The office cable required to extend the circuit terminal to the switching point (switches or switchboard) modifies the input impedance of the circuit. Also, there are different amounts of cable in different circuits and this difference may be great enough to impair the office return loss. Where the impairment is too

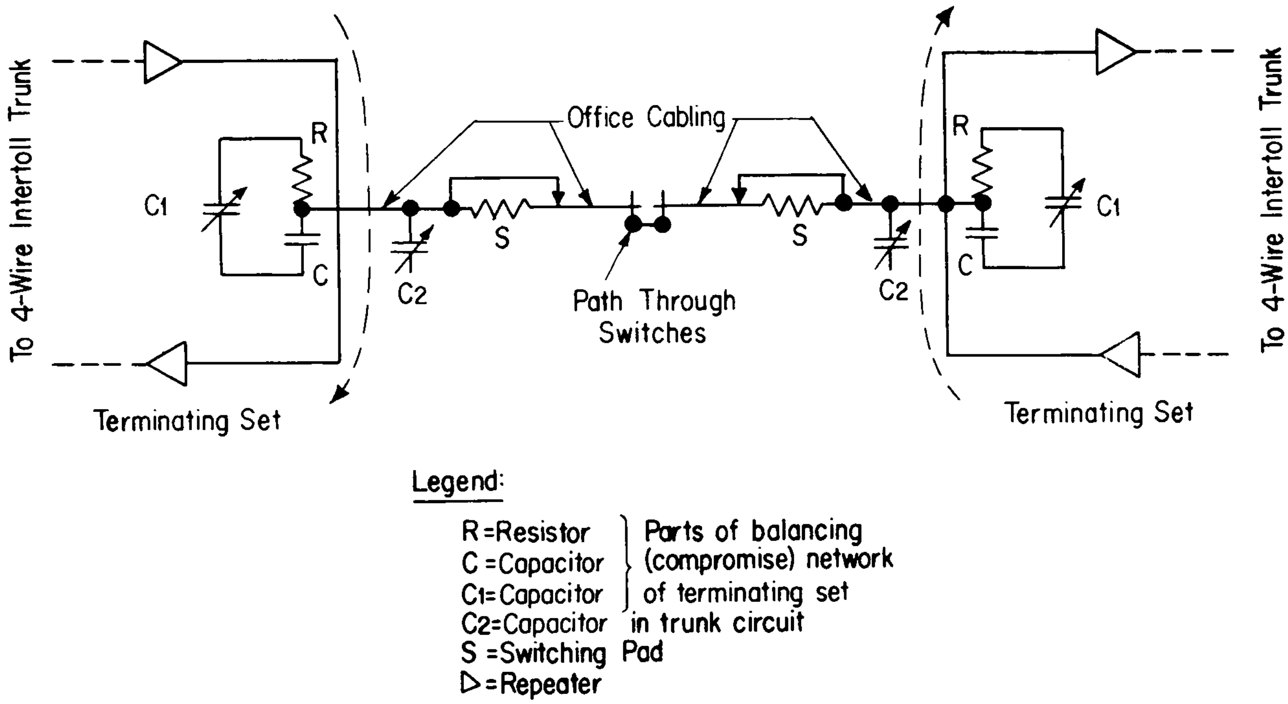


Figure 7-11. Typical Connections of Two Intertoll Trunks at a 2-Wire Switching Office.

great, the capacitance of each switching path is adjusted to a uniform value by means of the capacitors shown as C_2 on Figure 7-11. (This is known as drop building out.) Having restored uniformity to the terminal impedance, the capacitor shown as C_1 on Figure 7-11 (known as network building out) is adjusted to a value such that the compromise network will balance the circuit terminal impedance as modified by the office cable and building out capacitance on the two circuits that are interconnected.

The over-all effect is satisfactory if the offices are engineered so as to keep the length of office cable to moderate amounts. In particular, if long series runs are necessary, the use of larger conductors is advantageous. Except in very small offices, conductors smaller than 22 gauge should not be used; 19 gauge is preferable in the tie cables. The practical design limitation is to restrict total loop resistance of all wiring and equipment between 4-wire terminating sets to 45 ohms in 600 ohm offices and 65 ohms in 900 ohm offices.

With the exception of a few isolated cases, the following summarizes the nominal switching impedances currently used in the Bell System:

Local offices	900 ohms	No. 5 crossbar - toll	600 ohms*
Manual toll offices	600 ohms	No. 4 type toll crossbar	600 ohms
Step-by-step intertoll	600 ohms	Crossbar tandem	900 ohms
No. 5 crossbar - local	900 ohms		

*A 900-ohm arrangement somewhat similar to the crossbar tandem system discussed above is being considered for possible ultimate use for CAMA applications to this system. The initial CAMA trunks will have 600 ohms impedance.

In some of the 4-wire terminating sets, no standard provision is made for adding drop building out capacitors. A case in point is the 4TRN used in the Type O and N carrier systems. Office balancing in this case usually requires terminating the carrier system on a 4-wire basis and providing an external 4-wire terminating set such as the 4TP, 4TR, or SD-96463.

If the average return loss for all the intertoll trunks is equal to 27 db or better, the 2-wire switching office may be considered to be equivalent to 4-wire switching. If this degree of balance is not achieved, a "B" factor is assigned to the switching office. "B" factor is the additional loss assigned to each intertoll trunk terminating at a 2-wire switching office to provide the same echo performance as with 4-wire switching. In other words, there is a transmission penalty whenever switching is done on a 2-wire basis unless the office can be balanced properly and maintained in balance. The B factors are as follows:

Average Office Balance	B Factor (db)
27	0
25	.1
23	.2
21	.3
19	.5
17	.8
15	1.2
13	1.7

It is desirable to avoid the need of assigning a B factor since this adds loss in each switched connection and, if occurring at a number of offices on a connection, will increase the number of calls that would be unsatisfactory due to the over-all transmission loss being too high.

Intertoll Trunk Design - (VNL)

Employing the concepts presented in the preceding discussions, the design loss for an intertoll trunk today can be stated by the following equation:

$$\text{Via Net Loss} = \left[\begin{array}{c}\text{Via Net Loss}\\ \text{Factor}\end{array}\right] \times \left[\begin{array}{c}\text{Length of}\\ \text{Link in mi.}\end{array}\right] + 0.4\ \text{db} + \text{B Factor}$$

More than one type of facility may be permanently connected in tandem to form a link. In such cases, the VNLF for each type of facility is multiplied by its length, and the VNL for the link is the sum of these products, 0.4 db, and the B factor.

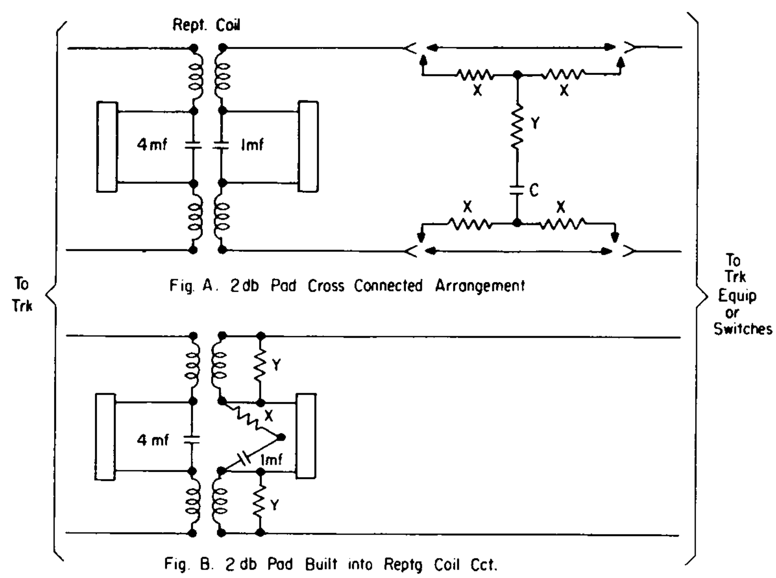
RC-RC Links equipped with Echo Suppressors will be operated at a loss of 0.5 db rather than their VNL

Toll Connecting Trunk Design - (VNL + 2 DB)

Under the nationwide switching plan as many as nine trunk links, including the toll connecting trunk at each end, may be encountered on a call between two end offices. It is evident that if the multi-link connections are to provide good transmission, all trunks must be designed and operated at as low a loss as is consistent with the transmission capabilities of the facilities involved (even though a call would rarely encounter the maximum of nine links). To achieve this, the VNL technique used in the design of intertoll trunks must be used in terminating link design.

In the development of Via Net Loss Factors, it was specified that a loss of 2 db would be provided at each end of the VNL designed intertoll circuit whether single- or multi-link. It has been the practice to supply this 2 db by a switching pad or by an equivalent increase in the loss of the end intertoll trunk. In present design, this pad or loss is omitted from the intertoll trunk, and a fixed pad (if required) is associated with the toll connecting trunk. This approach makes the design objective for all toll connecting trunks (as terminating links in the nationwide switching plan) a loss of VNL + 2 db.

When a toll connecting trunk has a loss of less than 2 db, a 2db fixed pad is inserted in the toll office end of the toll connecting trunk. As shown in Figure 7-12A, this pad is usually a simple resistance H-network



DESIGN VALUES FOR PADS

Fig.	Imped.	Resist. Ohms (± 2%) X	Resist. Ohms (± 2%) Y	C - mf (± 10%)
A	600Ω	34	2560	0.25
	900	51	3855	0.25
B	600	123	1160	1.0 } Assoc. with Rept. Coil
	900	185	1740	1.0

Table 7-12. Fixed 2 DB Pad Arrangements.

with a small shunt blocking capacitor. The pad should be located in or adjacent to the trunk equipment, and should have an image impedance equal to the impedance of the circuit in which it is inserted. Some types of trunk circuits will not accommodate the additional series resistance of the H-network. In such cases, the arrangement shown in Figure 7-12B can be used.

Where at least 2 db line loss exists in the toll connecting trunk, this will serve as the basic 2 db loss required by the VNL design. Omission of the S pad (rather than just moving it from one side of the 2-wire switch to the other) has the effect of reducing the terminal return loss by 4 db. If the balance between the toll connecting trunk and the office is inherently poor, measures must be taken to improve the return loss.

The improvement in over-all transmission obtained by eliminating the S pad loss or moving it from the intermediate to the terminal link is illustrated by Figure 7-13.

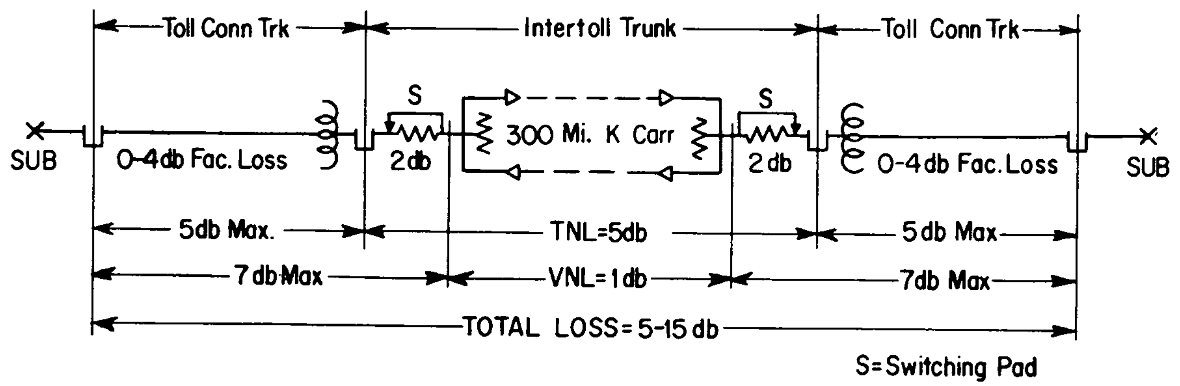


Fig. A – Intertoll Trunks Terminated at Terminal Net Loss

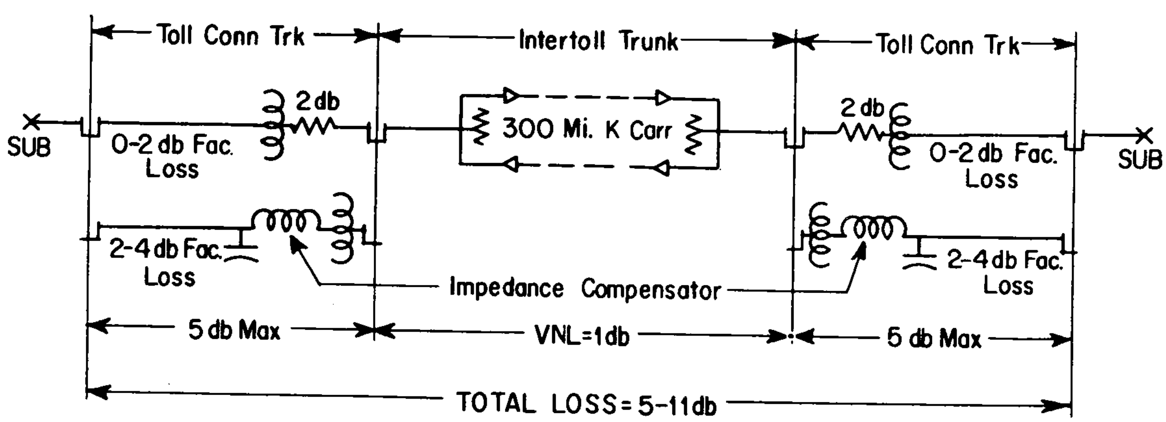


Fig. B – Intertoll Trunks Terminated at Via Net Loss

Figure 7-13. Benefit of Transferring Pads From Intertoll To Connecting Trunks.

Impedance Compensation

The portion of a loaded cable between the central office and the adjacent loading coil is known as the "end section". It is common practice to make the end section about one-half the nominal loading coil spacing, or to "terminate mid-section".

The impedance at the end of a loaded cable pair is a variable which is determined by two things, end section length and frequency. The cable impedance is matched to the impedance of the office equipment by inserting a transformer of suitable ratio between the two. This transformer is selected to match the impedances at 1000 cycles. As a result, the return loss of compromise networks against toll connecting trunks is good at 1000 cycles. Frequently it is 20 db or better. However, at 3000 cycles the return loss may be as low as 9 db. This is because at mid-section the cable impedance is a resistance that increases sharply with increasing frequency — the matching ratio of the transformer is independent of frequency — and the impedance of a compromise network is substantially constant.

Impedance compensation (or compensated loading) is an artifice to improve echo return loss by making the impedance of a loaded cable substantially constant above about 1000 cycles. This is accomplished with an adjustable

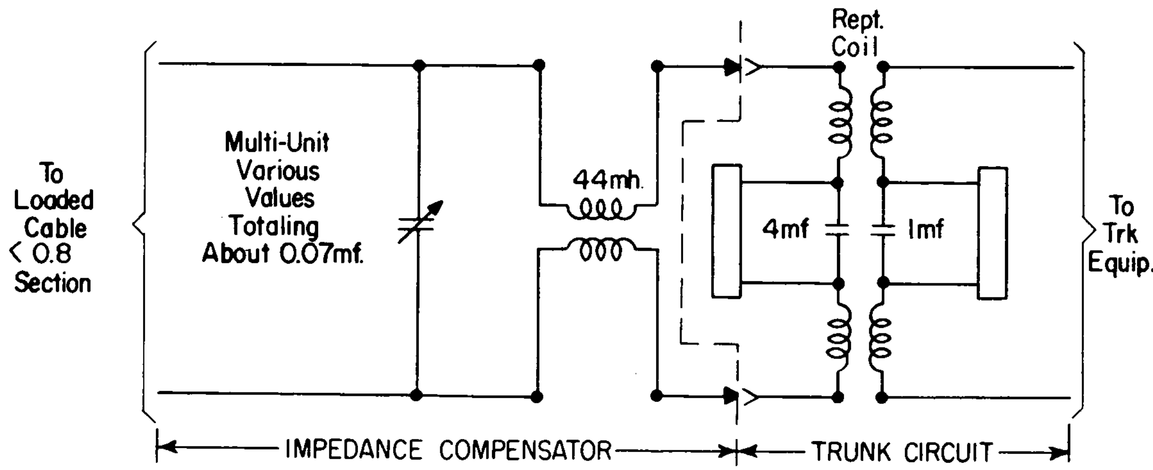


Figure 7-14. Arrangements Showing Application of Impedance Compensator.

capacitor and a loading coil as shown in Figure 7-14. Sufficient capacitance is bridged across the cable pair to build out the end section artificially to about 0.8 of a full-section. At 0.8 section, the cable impedance is a resistance in series with a capacitance. The resistance is constant, but the capacitive reactance increases with increasing frequency. The inductive reactance of the loading coil also increases with frequency. By choosing the proper size of coil, the inductive and capacitive reactances approximately cancel. The net effect is to make the cable impedance (as seen through the impedance compensator) appear to be a reasonably constant resistance throughout the critical echo range. This resistance can be matched to the compromise network, and return loss characteristics are materially improved at the upper frequencies.

The adjustable capacitor should be located adjacent to the cable pair so that it will directly augment the cable pair capacitance. The compensator normally is cross-connected between the MDF and the incoming or outgoing trunk circuit, or the switches if no trunk circuit is provided.

"Going To VNL Operation"

The equipment rearrangements and additions usually required to make an office suitable for Via Net Loss transmission may be summarized as follows:

a. S pads are removed from intertoll trunk equipment.

b. Primary Centers, and offices of higher rank, require an average office balance of 27 db (with a standard deviation of 3 db or less). Two-wire switching offices having a lower balance usually require office balancing.

c. Terminal links having a 1000 cycle facility loss of less than 2 db require a 2 db pad at the switching point.

d. Loaded terminal links having over 2 db 1000 cycle loss do not require pads, but must be equipped with impedance compensators.

e. Non-loaded terminal links usually require 2 db pads regardless of facility loss.

f. Terminal links operated on carrier and those equipped with hybrid-type V.F. repeaters require no special treatment. (Links employing E-type repeaters are treated as if they were non-repeatered.)

g. In trunk equipments using 120-type coils, the drop side blocking capacitor is made one microfarad to improve low frequency return loss. (See Figure 7-14.)

h. Operator telephone sets usually require a modification in the receiver circuit.

Idle Circuit Termination

When S pads are disassociated from intertoll circuits and these circuits are operated at Via Net Loss, the probability of singing during switching and idle circuit periods is greatly increased. This is particularly true at two-wire switching offices where the compromise networks cannot balance an open or short circuit impedance which may be presented to the circuit terminals during these periods. Consequently, idle circuit terminating impedances (usually similar to compromise networks) are generally provided for all four-wire and two-wire repeatered trunks at two-wire intertoll switching offices.

CHAPTER 8

"TRANSMISSION ENGINEERING FOR THE FUTURE"

We have had a look at some of the tools for doing the transmission job — how circuits tick, what some of the equipment will do, a few of the ground rules for making a system talk. One more thing is required, a philosophy for using these tools so that the transmission job we do today will pay dividends in the future. Harold Huntley gave a talk on this subject to a group of Operating Company people while he was Transmission Engineer at "195". The talk has been distributed in pamphlet form. But it is such a clear statement of this philosophy that it has been made the body of this Chapter. Even if you have read Mr. Huntley's remarks before, they may take on new meaning in the light of the preceding discussions.

Someone — a philosopher, probably — has remarked that nothing is permanent except change. Whatever its source, that remark is something more than just an amusing paradox. It's a daily condition of life for the telephone engineer. He is a man who works always midway between what is here now and what is to come. The telephone engineer has to think around the corner — not just the next corner, but the next after that and then still the next. In his planning he is constantly standing on tiptoe, peeping over the edge of tomorrow, trying to out-guess a future he can't see but must prepare for. He must prepare for it intelligently, economically, practically.

The only road to such planning — to *finding the right answer, now, for tomorrow* — lies through a solid appreciation of the best we have today, and the best ways to use it. The next step takes us into tomorrow.

The big words are *flexibility* and *imagination.*

These, applied fearlessly to present things — telephony itself, teletypewriter, data transmission, computer control, television of all kinds, electronic switching, carrier and repeater techniques — will give us a communications system useful for future things as well, and not one obsolete with the next turn of the calendar.

The man who has some very pertinent things to say about engineering for the future — things you can read simply by turning the page — is Harold Huntley, A.T. & T.'s Transmission Engineer, who for a long time has worked with one foot planted firmly in the present, the other in the future.

We think you will find that what follows is an unusually useful guide toward practical planning today for tomorrow — a guide for *all* branches of our communications industry, to help implement the imaginative engineering we must have to prepare for the future.

December 1955

C. M. MAPES, *Assistant Chief Engineer*
American Telephone and Telegraph Company

TRANSMISSION ENGINEERING FOR THE FUTURE

By Harold R. Huntley

Obviously, the title "Transmission Engineering for the Future" is redundant since all engineering is for the future — at least for the time it takes to engineer and install facilities. What I want primarily to talk about is how we can engineer plant today so that it will earn its way and provide a high degree of customer satisfaction for many, many years, regardless of what happens.

Now, there are no rabbits to pull out of the hat, nor formulae into which one can drop a lot of assumptions, turn a crank and come out with the right answers. No one knows specifically what the future holds. But I do believe that if we engineers are imaginative enough and forward-looking enough and can make effective use of history, we can do almost as good a job in preparing for the future as if we *knew* what would happen.

This will be the theme of my talk.

It is very important that we engineer for the future in such a way that, come what may, we will be prepared for it. We are playing for big stakes and we are unique in that if we make mistakes they live to haunt the business for generations. Let me illustrate.

> As a group, the several thousand engineers in the telephone industry are responsible for buying a billion or more dollars worth of plant each year with money which belongs to the owners of the business or is owed to people who have lent money to the business. The plant these engineers buy today — and every day — determines in large measure how good the service will be and how happy the people who put up the money will be and how happy the customers will be for many years. These engineers must, therefore, look at every job they do from this standpoint; they need to do the best possible job for the future as well as initially, else they may save a nickel today at the cost of a dollar tomorrow, or they may spend a dollar today on plant which will be worth only a nickel tomorrow.

Nobody can tell these engineers what plant to buy and where to put it; all that top management can say is what they want accomplished in general and how much money there is to spend; all that Traffic and Commercial can say is how many customers and how much business they expect and roughly how they expect it to be distributed. The engineers are the only people who can translate these factors into how much of what type of plant should be bought, and where it should be put.

It is a job of the first magnitude.

So our job is to plan for the future. And we know three things about it:

1. Quantities probably will be different from those currently estimated.

2. The instrumentalities will be different from those now known or even foreseen.

3. The needs and tastes of our customers will be different from what we now think.

Now, I do not want to get into any discussion as to the accurate forecasting of quantities. This is a subject being considered by people who have far better crystal balls than I. But I do believe that engineers would be well advised to do their planning in such a way that if quantities should turn out, say 20 years hence, to be a little different from estimates, they would not be in a hole.

One thing I am certain about is that instrumentalities will be different in the future, and that failure to take this fact into account can be just as costly as failure to take account of the fact that quantities may change. The changes in needs and tastes of the customers are even more difficult to predict. But if we plan soundly we will at least be in the best possible position to meet whatever comes up.

GENERAL OBJECTIVES

If we are to plan effectively for an unknown future with unknown instrumentalities, we must first have some broad objectives to guide us.

Now, I am going to confine my remarks pretty much to transmission and transmission instrumentalities, because that is my specific business. We'll touch a little on switching, but only as it affects our transmission thinking.

In the transmission end of the business we have stated our broad objectives on many occasions and they needn't be dwelt on here, but it may be well to summarize them thus:

Talking over the telephone must be so easy and pleasant that people will want to do a lot of it and that more and more of them will want telephones in order to be able to do so. This is fundamental and is as much a part of merchandising as color or gadgets.

The cost to the customers of having telephones and talking over them must be low enough so that they will think it is a bargain.

There must be enough profit so that a sizeable number of these customers will invest their money in the business.

Now, in planning for these things we must always remember that it is our customers (real or potential) who will determine whether or not the service is attractive, whether or not it is a bargain and whether or not it is worth investing their money in; not *we*. And we must always keep in mind that something people approve of today may be in quite the reverse situation tomorrow.

This fact is so obvious and there are so many examples of businesses which have failed (to their sorrow) to take it into account (and of others who have made good use of it) that it would hardly be worth talking about except that we may derive some further principles to guide our engineering for the future. Regardless of what future conditions may be, we will be doing our best to keep our business attractive, a bargain and financially sound if we follow these simple principles.

1. We must continually drive to improve the ease and convenience of talking over the telephone.

2. We must continually drive to keep costs as low as possible.

3. We must continually drive to keep our thinking and our plant flexible enough to meet whatever may come up in the future.

So now we have the whole story.

But we still need some measure of how easy and convenient customers think it is to talk over the telephone. At present — and for some years in the future, although we can begin to see the end of it — the best measure of ease of talking is the ratio between the loudness of the sounds in the listener's ear and the loudness of the sounds at the talker's lips. The loudness of the sounds reaching the listener's ears is a reasonable measure of how easy it is for him to hear. The loudness of the sounds which the talker has to put out in order that the listener may hear easily is a measure of how hard he has to work. The ratio of these loudnesses is a pretty good over-all measure of the combined efforts of the talker and listener.

The loudness ratio on typical calls has improved greatly in the past and we can reasonably expect it to improve further in the future. Figure 1 compares this ratio today with conditions 25 years ago and makes a prediction of what we expect it to be five or ten years hence.

Based on observations made at the Bell Telephone Laboratories in which a large number of people were asked to tell how well they liked different loudnesses in their ears, the typical ratios shown on this chart for "now" would be considered to be reasonably good by most people but a few would consider them only as fair. Considering the wide range in ratios which exist on different connections, it is not surprising that customers consider a small, but significant, number of present day calls as poor.

PROGRESS IN MAKING IT EASIER TO TALK

	APPROX. RATIO OF LOUDNESS (1) - TALKER'S LIPS TO LISTENER'S EAR	
	TYPICAL LONG DISTANCE CALL (2)	TYPICAL LOCAL CALL (2)
25 YEARS AGO	45 TO 1	30 TO 1
NOW	20 TO 1	13 TO 1
5 - 10 YEARS HENCE	6 TO 1	4 TO 1

NOTE:

1. WEIGHTED FOR BANDWIDTH; SIDETONE, ETC.
2. INDIVIDUAL CALLS MAY DIFFER CONSIDERABLY FROM "TYPICAL" VALUES.
   PRESENT RANGE IS ABOUT ± 3 TO 1 FROM FIGURES. RANGE WAS GREATER IN PAST, WILL BE LESS IN FUTURE.

Chart 1

The "typical" ratios shown for five to ten years hence are roughly equivalent to talking at a few feet apart in open air — like talking across a desk. Assuming that peoples' ideas do not change too radically during this period, these typical ratios will be considered as good by most people and as excellent by some of them. There will still be some calls which will be rated as poor, but they should be relatively rare.

So I think I can say that we can see the time approaching when, while we will still be interested in further improvements in loudness ratios, our main preoccupation will be to make talking more convenient and pleasant.

Already many customers want to talk over the telephone without holding anything in their hands — and this hands-free method will be as sure to spread as clutchless gear shifting is spreading in the automobile field. Maybe some years hence people will also want to *see* as well as *hear*. And in addition to talking (and possibly seeing) there will undoubtedly be a whole host of new requirements for high speed teletypewriter, data transmission, facsimile, operation of computing machines, television of all kinds — fast, slow, color, plain, and maybe even 3D — and nobody knows what else.

But whatever comes, it is our job to provide for transmitting it.

GENERAL PRINCIPLES OF DESIGN

Now, how do we go about the job.

In the transmission business we have, for several years, had some basic ideas with regard to how to do this even for an unknown future. What we shoot for is to have all of our talking paths with the following characteristics:

1. They should be cheap, rugged, good and capable of transmitting a reasonably wide range of frequencies with small distortion.

2. They should be capable of operating at very low transmission losses.

3. They should be on wheels so that we can move them around to follow changing traffic patterns.

We have not yet devised a method literally of putting our circuits on wheels, so we have to derive from this basic objective a practical working plan. And the principles of this plan are very simple. They are:

1. We must work eternally for cheaper and better telephones and repeaters and carrier systems, because this is the only way to have low costs and low losses simultaneously.

2. We must work eternally for a minimum of plant that can't be moved, and for a maximum of the things that determine service and cost easily movable by putting them on a plug-in basis.

This plug-in concept started some years ago primarily as a method of facilitating maintenance and keeping circuits in service. However, as we have gone along we have come to look upon it as a cornerstone in forward planning because it gives a degree of flexibility that could never be approached by fixed plant.

Having stated our general objectives and methods, let's get down to their specific application. But first let's divide the whole job into two parts: loops and trunks. Chart 2 shows this division. The reasons for this division are that both the problems and the instrumentalities are quite different in loops and trunks.

I would like specifically to call your attention to the fact that in trunks we are *not* differentiating between toll and exchange. The reason is that the instrumentalities and methods used in toll and exchange trunk design are rapidly becoming the same, and as a matter of fact, it is only tradition that separates them now.

Our problem is, of course, to design the loops and the trunks so that any possible combinations of customers in areas A and B will find it easy and pleasant to talk to each other regardless of where they may be located in their

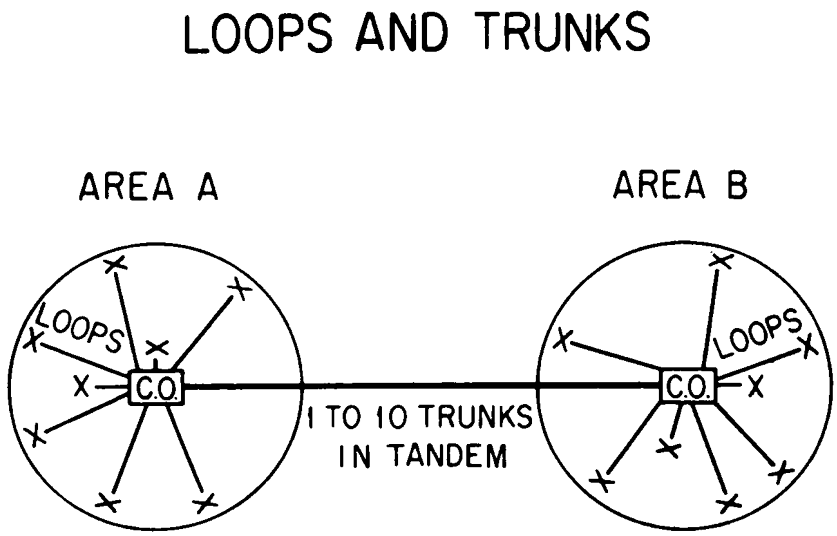


Chart 2

areas, and regardless of whether A and B are in the same town or several thousand miles apart, and regardless of how many trunks there may be in tandem between them. And we must do it at the lowest practicable cost, by the practical applications of the principles I have already stated.

TELEPHONES AND LOOPS

One of the most important instrumentalities in telephony is the telephone itself. There are about 95 million of them in the world — over 50 million in the Bell System and other Companies connected to the Bell System — and at least two of them are involved in every call. The transmission improvements in telephones are among the most important factors in the over-all improvement in ease of talking, and in keeping costs under control. Because this is so I thought you might like to see how much improvement there has been in the transmission performance of telephones in the past 25 years.

The curves in Figure 3 show comparative responses over the frequency range of a typical telephone connection (loops only) using typical sets which were in use in the Bell System in 1930, 1945 and 1955. The improvements are, I think, evident. Now, what have these developments brought us, and what of the future?

In the first place, they are responsible for a large part of the improvements in "loudness ratio" which I have already shown you. In the second place,

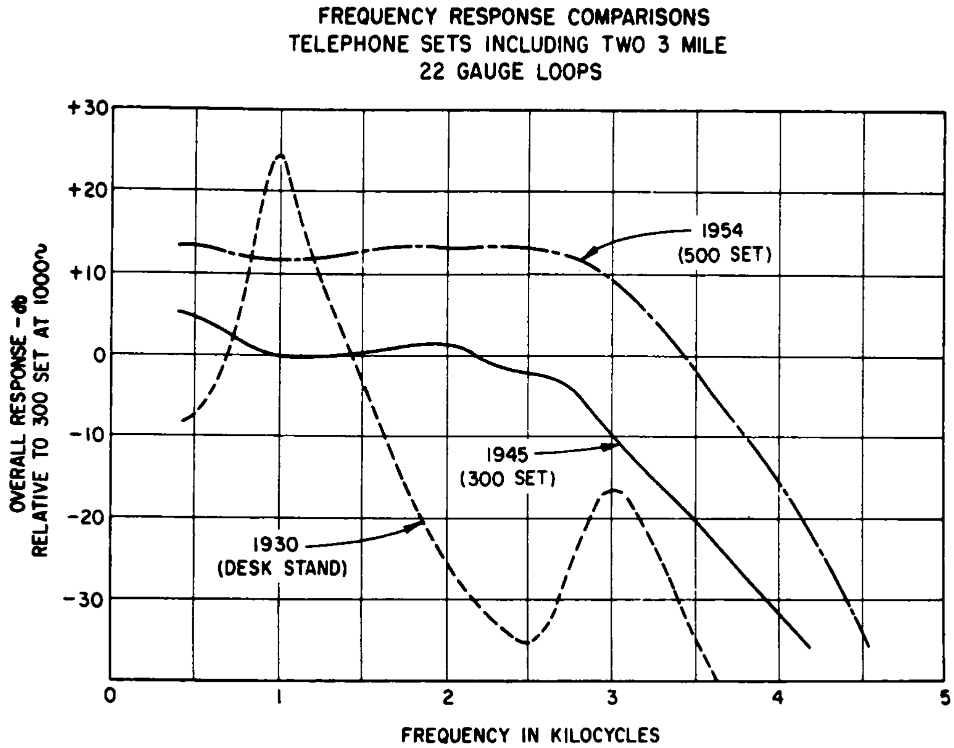


Chart 3

the transmission efficiency of sets is now great enough so that loop cable gauge is controlled by signalling. And signalling ranges are fairly lenient so that we can make substantial economies through two things:

1. We have great flexibility in the locations and sizes of switching installations.

2. A very large proportion of our loop cable plant can be fine gauge; at least 50% can be 26 gauge, with most of the remainder 24 gauge.

The end obviously is not yet. There are several things which will have a marked effect on the loop plant of the future. One of these is a potential large extension of signalling ranges through electronic signalling methods (which may or may not be associated with electronic switching, as such) which will let us signal over much longer lengths of fine wire.

Along with this will come electronic amplifiers in telephones, which will let us talk adequately over these higher-loss loops. Then there is electronic switching itself, which, along with line concentrators, may radically affect the desirable numbers and locations of switching centers and the sizes and locations of loop feeder cables. Maybe, by that time, we will be using carrier in our loop plant, and will have carrier and concentrators working together. Along with this as a minor complication will be the thing I mentioned previously — some future improved version of the "speakerphone".

I would like to be able to say that with all of the electronic developments, we will have an easy solution to the loop cost problem. But I am afraid it will remain a tough, dirty job for many, many years. For one thing, we still have the problem of getting an individual circuit from the Central Office (or at least the last concentrator) all the way to and into each customer's house (or at least to the houses of a small group of customers), and any way you slice it, it is a tough job. In the second place, changes in customers' needs and views are reflected immediately in loop plant design, so we have to be prepared for almost anything. The first man who comes up with a good, cheap and extremely flexible wide band carrier system for loop plant use will live in the hearts of all transmission people for generations.

To come back to earth, it seems to me that there are two things which we must do now in our planning for the future. First, we must continue to drive our trunk losses down so that loops will have the easiest possible job. Second, we must be increasingly on guard against using loop conductors bigger than are necessary because whatever the future holds it certainly will not be in the direction of requiring larger conductors in ordinary cable pairs.

We must do one other thing. One of the penalties of using a minimum of fixed plant is that the gadgets which make up the transmission must be used in the proper numbers and in the proper places; that is, we can't *both* cut down the fixed plant and leave out the gadgets. This is a general principle which goes through the whole transmission engineering problem. Applied specifically to loops we can state it this way:

> If we are going to use the finest possible loop cable conductors, we must have the right sets in the right places. We can no more have the right grade of service without having the right sets in the right places than we can if we don't have the right types and quantities of switching gear. And let's not forget that if we need loop loading we should put it in.

TRUNKS

I have not yet disciplined myself to the point where I don't have a great feeling of relief when I get out of loops and into trunks, because, in trunks, we have gone a long way in cutting down physical plant and getting our instrumentalities readily movable. All we have to do for the future is to do more of the same.

As a matter of fact, we are in such a favorable position with respect to trunks — and the outlook is so bright — that I am going to propose seriously that we begin *now* to orient our long term planning in the direction of operating at least our trunks which are *not* involved in nationwide connections at or very close to zero loss instead of the 4-6 db range we thought was somewhat radical less than two years ago. This will be our greatest contribution to keeping over-all costs down because it will give us the greatest possible flexibility in location, number and type of switching centers, and the greatest possible freedom in loop plant design. Carrier or fine wire with repeaters is the cheapest way to provide new trunks more than a few miles long, so that for such trunks low losses don't cost any more than high losses; all they cost is engineering brains. For trunks under about five or six miles, (and occasionally for longer trunks), we can't do it economically yet, but we should not lose sight of it as an *objective*, because some day it will be possible.

We can prepare for this condition simply by sticking eternally to the principle of minimum fixed physical plant and the maximum of movable plant. (Incidentally it will also do more than anything else to ease a lot of problems which plague us, like speakerphones, operators' transmission, etc.).

I wish I could propound the same philosophy of zero loss with regard to trunks which *do* get mixed up with nationwide calls, but I must take a rain check on them. These trunks must always have some loss so that when several of them get connected together by the machines we don't run into difficulty because of such things as echo, crosstalk, etc. How this minimum loss is determined is beyond the scope of this talk, but your transmission people can tell you if you want to know. And let's be sure that just because we can't drive these trunks down to zero, we don't hold back on other trunks.

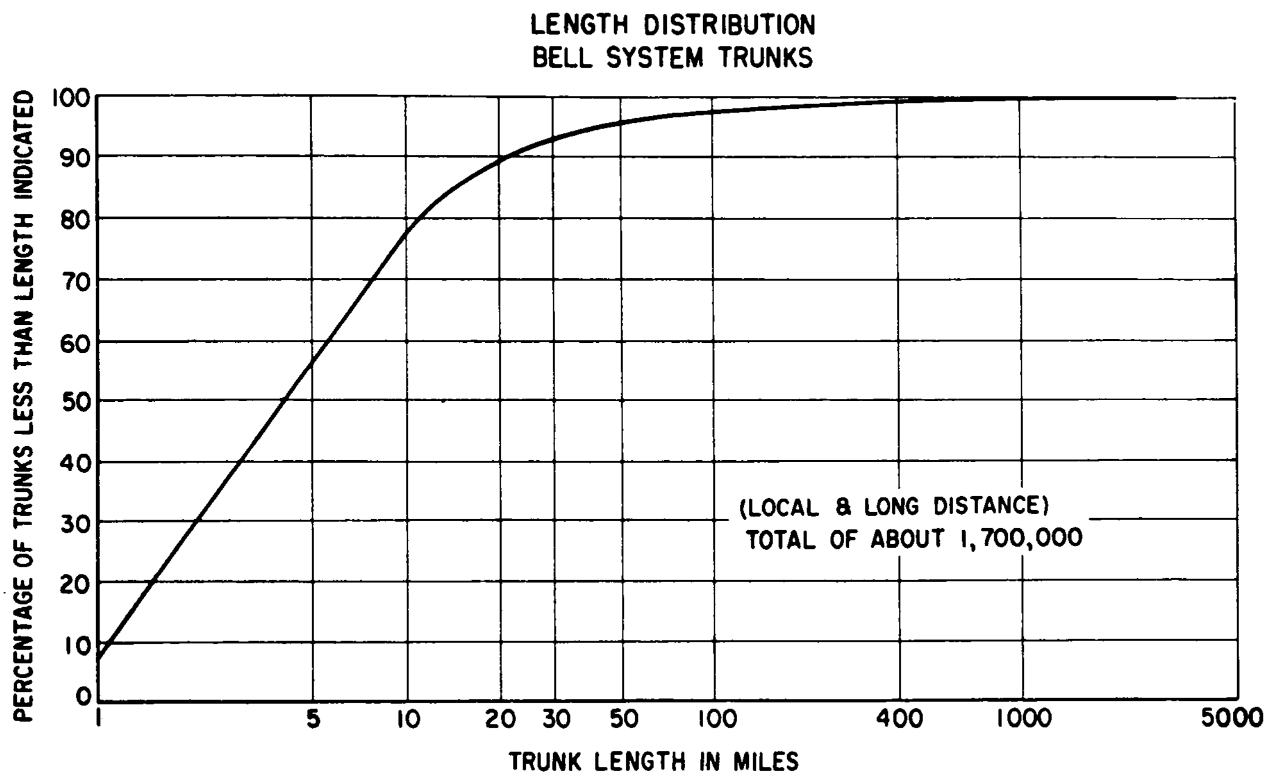


Chart 4

Where the Problem Lies

To get an idea of where the work is, consider Chart 4. This chart shows the proportion of trunks (both toll and exchange) in the Bell System less than any given length. For example:

92% (1.5 million) under 25 miles.
78% (1.3 million) under 10 miles.

So, there is no question but that the job lies in the shorter length ranges. And now let's look at this part of the length range in more detail.

What we need to do is to gear our thinking in this length range along the same lines as we have been accustomed to in the longer haul field for many years. In the longer haul field carrier is "old hat;" nobody even thinks about putting in anything new except carrier. While questions may occasionally arise about what kind of carrier or what kind of base facilities (e.g., radio or wire) to use, questions about whether good transmission can be proved in are conspicuous by their absence. While carrier is not the sole answer in the short haul field, we must gear our thinking to the principle that transmission is a function of electronic gear and conductors are only a means of connecting one set of electronic gear to another.

It has been easy for many years to see that the fulfillment of this kind of concept was coming; one only had to watch the progress of electronics to be certain that some day the circuit without electronic gear of one kind or another would be the exception rather than the rule. But I will be the first to confess that it has been — and still is — difficult fully to comprehend the tremendous impact of the developments in, and cost reductions of, repeaters and carrier which have occurred within the past two or three years. In two or three short years these things have changed our concept of trunk engineering in the short haul field from one in which it was axiomatic that the better the transmission the more it cost, to one in which we can give good transmission either at no excess cost or at costs which are so low that we don't have to worry about them. In all my experience in transmission business I have never seen such a radical change affecting such a large segment of the over-all problem in so short a time.

I am convinced that proceeding along the line of minimum physical plant, with transmission being the responsibility of electronic gear, will be more effective in keeping trunk costs down and giving the best possible service in the years ahead than any other method. While, up to this time, electronic gear has only been able to soften the effect of cost inflation in the shorter length range, maybe some day it will be possible to lick it as we have done in the longer ranges.

Now, let us document at least partly what's been said.

Figure 5 shows for average conditions a rough comparison of the costs of providing 3 db trunks by various methods in the length range up to about 30 miles. (The bumps in the curves are where we put in repeaters and long line signalling equipment.) And while "average" conditions, like the "average" man, never exist, we can draw some general conclusions from this Figure.

First, we can say that even with today's repeater and carrier costs we can't lose money by sticking to the fine gauge-repeater-carrier concept. All we have to do is look at history to know that the long term trend is bound increasingly to favor electronic gear, and to know that if we follow this plan we will be even better off as time goes on. We know that in many cases at least, the deviations from average conditions are such as to favor the electronic concept.

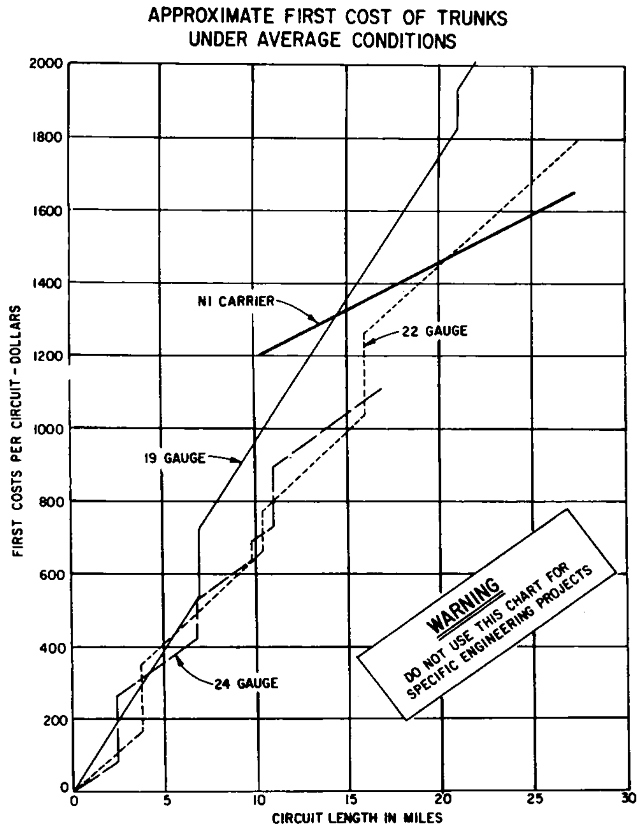


Chart 5

The second thing we can learn is that while the number of repeaters we have to buy is affected to some extent by the losses to which we design the circuits, if we stick to reasonable losses the over-all cost of the plant will not be greatly affected. Working to higher losses moves the "bumps" further to the right and thus cuts down the number of repeaters used in the shorter trunks. Actually what may be a sensible approach in many cases is to use about 3 db as a temporary criterion as to whether or not to use repeaters on toll connecting and tandem trunks of the usual variety, and 6 db as a temporary criterion for ordinary interoffice trunks, with the idea that more repeaters can be added later. But the loss of any trunk on which repeaters are used at all should be as low as practicable because it will give better service and will cost no more.

The third thing we can learn is that there is an economic battle royal going on between carrier and repeaters. That is, any reduction in the height of the bumps would give repeaters a greater edge and any reduction in carrier costs would greatly extend its field of use. This seems to be an ideal situation because we can't possibly lose, whatever happens.

Carrier vs. Repeaters

Just a word about this battle between carrier and repeaters.

While it isn't too important which has the advantage at any particular time, I will confess that I am basically a "carrier man". And I am going to urge that whenever carrier has anything like an even chance of proving in, you give it the breaks. My reasons are simple.

1. Carrier takes less fixed outside plant (and, hence, is more flexible in caring for future changes) than any possible fine wire-repeater combination, at least using present types of cable.

2. Carrier prices will doubtless go down (at least relative to the general price level) so that caring for growth by putting more channels on existing cable pairs will be cheaper as time goes on.

3. It is fundamentally better from the standpoint of handling both present and new or unusual transmission problems.

We might say a word here about this last item, and then discuss it in more detail later.

I am not worried about ordinary telephone transmission over repeatered fine-wire circuits up to lengths of around 25 miles, and carrier proves in hands-down above these lengths. But I am worried about possible growth in the need to transmit a wide range of pulse systems not only over special circuits but also over some of the types of circuits provided for regular telephone service. These systems range all the way from telegraph speeds to quite high speeds, and may involve a wide range of services including such things as data, facsimile or slowed-down video*, etc.

Repeatered circuits always have more circulating currents than carrier; these currents are relatively harmless so far as ordinary telephone transmission is concerned, but may be murder so far as pulse transmission is concerned. This problem is not controlling at the moment, but is worth keeping in mind in making a decision between carrier and repeatered circuits. We'll return to this pulse matter later.

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*Slowed-down video means transmission and display by television techniques of (usually) stationary and relatively simple pictures, such, for example, as signature, figures, etc.

By transmitting at low speed, much narrower band widths can be used than for normal TV.

Low Cost Installations

Now, I would like to sound one warning note: cheap electronic gear will not get us cheap circuits unless we do two things:

1. We get the cheapest possible installations.
2. We get the cheapest possible regular and standby power supply arrangements.

With regard to both of these things, we must be ingenious if we are to obtain low costs. For example:

> My own private objective would be never to spend more for power specifically devoted to electronic gear than something like 1/4 of what the gear costs; I might not always make it, but I certainly would give it a try. If, for example, we had less than 50 E23 repeaters** to put in we would supply the 130-volt power through a rectifier from the commercial power supply with one of the available cheap vibrator jobs supplied from the normal 24- or 48-volt C.O. battery to carry over for a few minutes or hours if the commercial power failed. I do not purport to be a power expert, but I feel certain that we can take care of the power requirements in many cases at a lot less cost than we have in the past.

The stakes involved in doing these jobs very economically are greater than just what we save initially; if we don't, we may figure that repeaters and carriers cost so much that we may go down the wrong path.

To Switch or not to Switch — That is the Question

Transmission does not operate in a world apart from switching. And the improvements in transmission instrumentalities have two opposing effects on switching plans.

1. They let switching people do almost anything they want to without any transmission restrictions; this tends to increase switching.
2. They make direct circuits more economical; this tends to reduce switching.

We can illustrate the problem by a Chart (No. 6). The problem is whether to switch all of the traffic between C and A (and probably thence to the world) at B or to handle all or some of it over direct circuits from C to A. This problem may arise in connection with decisions regarding tandem CDO's or regarding what office to "home" another one on; I am *not* talking about the automatic alternate routing principle.

**An E23 repeater consists of both a series negative impedance element (E1 or E2) and a shunt negative impedance element (E3) used together.

TO SWITCH — OR NOT TO SWITCH

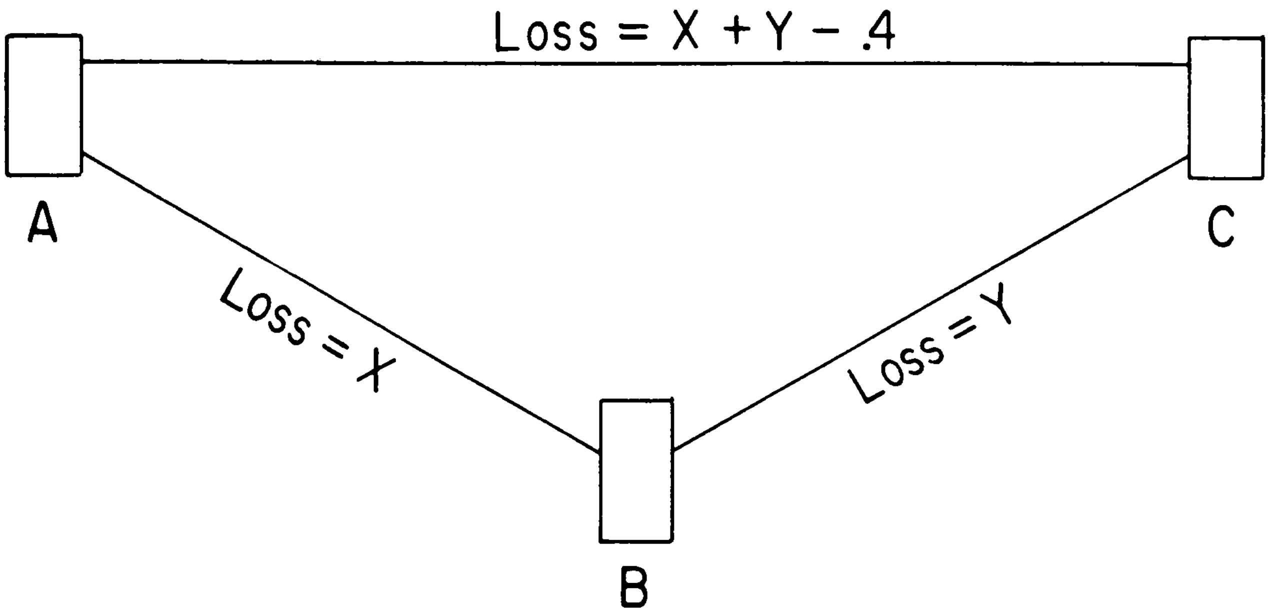

Chart 6

Consider first the transmission aspects.

If, as frequently happens, the direct circuits from C to A would be about the same length as the sum of the C-B and B-A circuits and would use the same type of facilities, the *design* loss over the switched connection would be only about 0.4 db greater than over the direct circuits. It is this reasoning that leads to the concept of handling traffic on a switched basis in order to obtain real or imaginary economies by taking advantage of the greater efficiency of large trunk groups. That is, if the C-A group is not established, the A-B and B-C groups will be larger but the increase will not be as large as the number of circuits which would be needed in the A-C group.

Let's look at the economies a little closer. For simplicity let's assume first that all of the circuits are long enough to use carrier. In this case each circuit between A and C will cost very little more than a circuit between A and B or between B and C. (See the carrier curve on Chart 5). In other words, a connection from A to C switched at B requires *two* carrier channels, each of which costs almost as much as the single carrier channel from A to C. In addition, it costs something to terminate circuits in the switching equipment at B and something for the equipment which must be added at B to handle the switched traffic. So, in order to save money by switching at B, one must have a much higher efficiency in the A-B and B-C groups than he would have in the A-C group.

There are two other less tangible but real considerations.

1. While the *design* losses give only 0.4 db difference, the problem of maintaining the circuits in the two groups so that they will work in tandem is tougher on the Plant Department than maintaining only the direct circuits.

2. Although I am not a switching man, I gather that while the digit problem with the added switch can be solved, switching people would be just as happy if they didn't have to worry about it.

We are not going to try to solve any specific case, but I do urge that you remember two things in your planning work.

1. An unnecessary switch never helps either transmission or switching.

2. In this carrier age, circuit cost goes up more slowly than length; one must use actual circuit costs in the specific situations rather than, say, average cost per circuit mile.

For the long pull, we must remember that whether to switch or not to switch depends greatly on the particular states of the switching and transmission arts and on the relative costs. At the moment, transmission costs appear to be sliding faster than switching costs, and this argues for more direct circuits and less switching. But this has not always been so in the past, and it may not always be so in the future. All one needs to do to see the marked effects of changes in economic balance between switching and transmission on switching plans is to consider the gyrations which have been gone through in the last 10 years in plans for nationwide dialing. We may fully expect that someday something is going to happen in switching which will have as radical an effect on costs as short haul carrier has had on transmission costs. When and if this happens we can look for drastic changes in our trunking plans.

But this need not worry us one bit. In the first place, such drastic reductions in switching costs can only be for the good because they work in the direction of lower *over-all* costs. In the second place, if we keep our transmission planning flexible enough and keep it on the basis of movability, we can economically take care of any changes which occur regardless of what they may be.

THE PULSE PROBLEM

I promised earlier to say something about the growing importance of pulses in transmission engineering. This does not refer to possible future pulse carrier systems about which you have probably heard a lot. We needn't be concerned whether our future carrier systems are pulse or not, all they need be is good and cheap. The subject right before us is future transmission of pulses over our regular telephone facilities and what it may mean in the planning we do today.

One thing which seems clear is that in the future we will have a lot more transmission by means of pulses or their equivalent over our circuits than we now think. And to see that, you don't have to look at the future through a telescope; just use the top part of your bifocals.

My guess is that in the next few years we will see a bewildering array of new forms of video, data systems, facsimile — and what have you. Some of them will be on private line networks (where at least we can do special things if we need to), but some of them will go over types of circuits provided for regular telephone services. We must keep our heads on our shoulders and not go into a dither to design new transmission systems every time a new problem comes up, or we will continually be like the General who "mounted his horse and rode off in all directions".

Now, why are these pulse jobs so worrisome? Simply because they require a high degree of precision in the *time* (as well as the losses) of transmission of all of the frequencies over a wide range (known to the initiated as "phase" and "amplitude" respectively) and because a short spurt of noise may put in an extra pulse or obliterate one that should be there, and because a single mutilated pulse may change the sense of an entire "word". Perhaps I can illustrate the problem this way.

In ordinary telephony, if the transmission gets a little distorted or the circuit is a little noisy, one doesn't hear as well and this may make him unhappy or even mad, but he probably won't hear different words than the other guy said. But in pulse transmission the addition or subtraction of a pulse or the displacement of any part of it may give an entirely different meaning to a "word". Another way to say it is that some of the newer and faster forms of pulse transmission may multiply the kinds of problems we encounter in telegraph transmission many fold.

From the broad transmission engineering standpoint we want to approach as closely as practicable to two objectives.

1. We want the circuits we use in private line networks to be the same (or very nearly the same) as those we would use between the same points for regular message service in order to have the greatest possible flexibility in patching, etc., and to limit the amount of work involved in laying out and maintaining circuits of special design.

2. We want to be able to handle the widest possible range or pulse systems over regular toll and exchange types of circuits.

So, the main question affecting our transmission planning for the future is whether the path we should follow in order to meet these objectives is the same one which results in the best and most economical regular telephone service.

And the answer seems to be "yes".

All that the possibility of future pulse transmission does is to add to the importance of doing the right kind of a forward-looking job along the lines I have discussed previously. More specifically it says things like these:

1. Stick to the fine wire and repeater and carrier concept because this gives the best and cheapest circuits, *but:*

2. Give carrier all the breaks you can, *and:*

3. Where the circuits are too short for carrier use E23 repeaters in place of E2 or E1 repeaters alone wherever you can economically, *and:*

4. Don't try to squeeze too much gain out of each repeater — either carrier or voice; put (or at least plan for) enough repeaters in a circuit and lay them out so that there will be some margin against circulating currents and noise, *and:*

5. Don't split trunk gauges unnecessarily and put the load coils fairly close to where they should be.

This all sums up to saying, don't chisel on the design too much. Not chiseling may cost a little bit more initially on some jobs but this excess cost will be small and will be less than the savings which are made by avoiding the use of big copper in the trunk plant. Even if you never send any more complicated pulses over the circuits than those which are used to control our own switching systems, your regular telephone customers will be a lot happier.

This kind of plan will result in a lot more occasions where the cutomers say (or at least think) "this is a really good connection" and a lot fewer where they say (or at least think) "where in the devil are you talking from?"

MAINTENANCE

Now, after all this talk about engineering, a few words about maintenance — because the whole future of what comes out of our forward-looking engineering rests on having the circuits perform the way we design them. This job is one that has taken — and will take — a lot of doing. This doing has taken, and will take, the best combined efforts — each in their own sphere — of the Plant and Transmission Engineering People. Let's look at the problem a bit.

Time was when great store was set by things which, in the vernacular, could be maintained "with an axe and a crowbar". Those were the days when the best circuit (from the Plant man's viewpoint) was a pair of open wires (preferably 8's) and anything more complicated in a switchboard than a simple relay was something to be looked at with suspicion.

Then came the repeater.

In the first years they were locked in cages and were accessible only to a chosen few. By the time they began to be looked upon as part of the plant, carrier came along. Between carrier and repeaters, the old concept of maintaining a circuit solely by *maintaining its physical integrity* went by the boards. Many people have mourned its passing and some people hardly believe that it has passed, but facts are facts, and there is no use worrying about it.

Maintenance on the basis of physical integrity only is based on the concept that a circuit either is O.K. or it is in trouble, and that if it is in trouble one can fix the circuit by fixing the trouble. This concept is good for such things as relays, which either operate or don't operate, or for many kinds of inert equipment, but it is not adequate in the transmission end of the business. Maintaining transmission circuits so that the service is good is a much more subtle problem; it involves a sort of sliding scale concept which asks *how* good the job is rather than just is it good or bad. And its solution cannot be found by the simple process of spending more money or pounding the table.

Perhaps the difference in concepts may be illustrated by likening them to a so-called black and white picture; the trouble shooting concept is like saying that everything in the picture is either black or white, whereas the transmission concept is that there are innumerable shades of gray between black and white and what we are shooting for is the lightest possible shade of gray. This concept becomes increasingly important as we go forward with our more economical but more complex designs of plant which have electronic gear as their basis. The better our transmission gets on the whole, the more critical will our customers be of occasion when transmission is not to their liking.

This, of course, is simply a reflection of the fact that peoples' judgment of what they like and don't like is conditioned by what they are accustomed to. For example, it's certain that many of the things customers now complain of would have seemed pretty good to them five or ten years ago. But we must improve transmission on the whole, and this brings with it the need to have *every* connection good.

So we need two things:

1. We need to keep closely in touch with how good transmission is from the customers' viewpoint through such things as customer opinion surveys, observation schemes, etc.

2. We need a step-up in the precision with which we maintain the performance of *every* circuit.

These problems are made more difficult by the fact that electronic equipment is necessary to keep our service improving and costs down, and that electronic equipment is adjustable. The Bell System has come a long way in the use of electronic equipment, but we will go farther and faster in the next few years than we have in the past. We have repeaters and carrier in about 150,000 circuits today, and it has taken us 35 years or so to get that many. If you recall one of my earlier charts, you will not be surprised when I predict that in 10 years or so, this number will be at least three times as big. And this does not count the impact of subscriber carrier, electronic sets and such like. In addition, we will have many more pulses and television and I don't know what else.

Now, it's no more possible to tell you what detailed techniques we will use in the future than tell the details of the instrumentalities we will have, but the principle on which they will be based is clear. That principle is that people — at least the kind who will be maintaining these circuits — consciously or unconsciously *want* to do a good job and what we must do is to make this "want" as effective as possible. This is, of course, not a new principle — nor is it unique to the telephone industry — but it has not always been recognized and developed. I believe we have been among the leaders in this regard — and we have ample proof that it is a potent method in our own field — but it is heartening to see that it is being increasingly recognized in many other places.

> For example, recently I went through a very efficient mass production factory — one where "automation" is not a word, but a fact — replete with "quality control" charts and all the paraphernalia necessary to make millions of complicated things at low cost. The thing that impressed me more than all of the marvelous tools and the organization of the work and the processes, was the fact that it was the machine operators and girls on the assembly lines who were the ones who made the most use of the quality control charts — not the inspectors or the "front office". As the Works Manager expressed it, "We want to *build* quality in — not try to *inspect* it in."

The solution, then, lies in *releasing* the native desire and ability of the maintenance people by training them in objectives and fundamentals (in addition to training them in detailed techniques) and giving them the tools so that they know *themselves* how good a job they are doing. This training must extend to their bosses, and their bosses' bosses, and their bosses' bosses' bosses all the way up the line, so that they will know and want the same things. It is a job in which the Transmission Engineering people can help mightily. This is not to imply that there is not already very close cooperation between Plant and Engineering people in many Companies. But all of us must accelerate our efforts, and we must put increasingly into practice those things we know.

THE TALE IS TOLD

Now, the summing-up.

I could — and maybe I should — end this story by the usual observation that never before in the history of the business have the transmission people been faced with as many problems as they are today. But if I did I would simply be saying something which would have been equally true last year, or ten years ago or 25 years ago, and which will be equally true ten years hence. Every year, in a business which is growing and in which the art is advancing, sees more problems added than are disposed of. But I think that in this particular period something new has been added. And it is this "something new" and its significance which I have been talking about and which I want to be sure to leave with you.

Up to a very few years ago electronics was pretty much confined to trunks over about 25 miles long; i.e., not over ten per cent of the total number. Installation of carrier and repeaters were few enough so that each one could be prayed over and studied at length by people who had grown up in the business pretty much parallel to the growth in electronics. Sure, they faced many new problems and certainly it was important that they did a forward-looking job. But the quantities they were dealing with were relatively small and electronics was their daily fare; they could look an electron squarely in the eye and say to it "phooey — you can't scare me." Now, all of a sudden we are talking about electronics in 40 per cent of the trunks instead of ten per cent. And this added 30 per cent is largely in a field where electrons are strangers and where until very recently, the only tools available to get db's out were to put more dollars into bigger copper and heavier loading.

But, in this year of 1955, trunk gauges and losses finally and irrevocably part company (at least for everything more than a few miles long); loss is independent of gauge and depends on brain power in the use of electronic gear. To say that this change in concept is a severe wrench in our thinking is to put it mildly. And when we think of the quantities involved and the economic stakes in doing the job right and what we can see in the future, we can scare ouselves half to death if we don't watch out.

So something new *has* been added, and it will get newer and more complex and more diversified as time goes on. We don't know what the future will bring in the way of quantities, instrumentalities and customers' wants. But we must go ahead; and we can do it successfully if we are imaginative enough and courageous enough and forward looking enough and will stick to our basic principles.

Perhaps I can sum it all up by paraphrasing some of the advertisements which are not uncommon these days, thus:

"More and better service to more people through electronics."

Good luck to you and your Plant Department friends.