The Lenkurt® Demodulator

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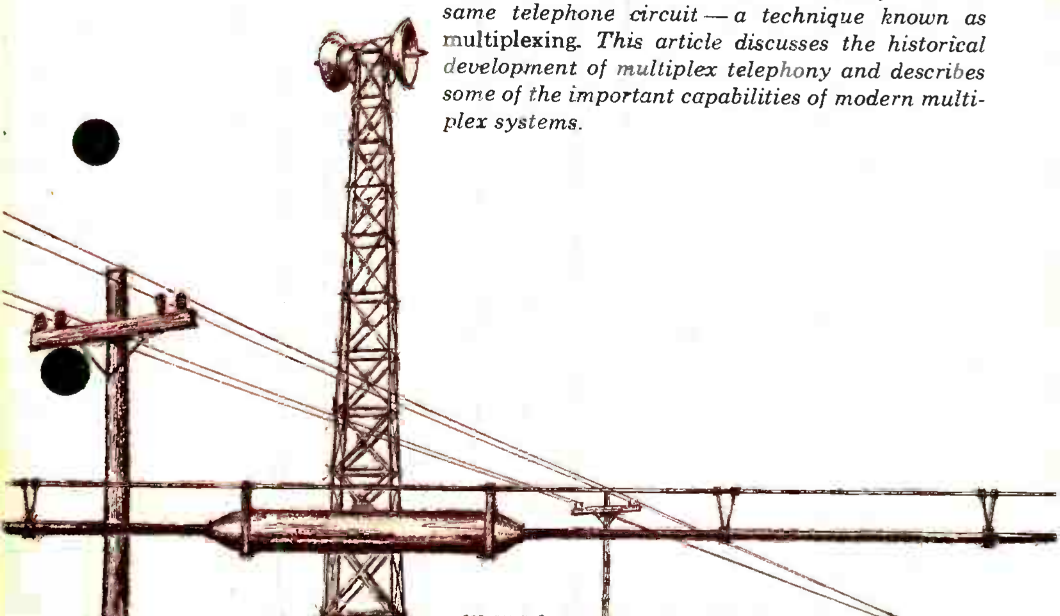
The Development of MULTIPLEX TELEPHONY

The advancement of telephone communications from a laboratory experiment to a highly sophisticated technology records some rather extraordinary achievements. Prominent among these achievements is a means whereby two or more speech signals can be transmitted simultaneously over the same telephone circuit — a technique known as multiplexing. This article discusses the historical development of multiplex telephony and describes some of the important capabilities of modern multiplex systems.



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The ability to transmit the spoken word over long distances by means of electrical circuits was indeed a revolutionary step in man's progress. Since Alexander Graham Bell's remarkable invention in 1876, the telephone has become a vital and indispensable element in promoting economic and social progress. Today, with millions of miles of telephone circuits, there seems to be no bounds on man's desire to communicate with distant places.

The first practical telephone circuits consisted of a single grounded wire with a telephone connected at each end. With this arrangement, each telephone could be connected only with the telephone at the opposite end of the circuit—and not to any others. Such a simple arrangement was very limited.

It didn't take long to realize that there was a need for some practical means of interconnecting all the telephones in a local area. This need was satisfied by establishing a central point where all local telephone circuits would come together and where any two telephones could be interconnected, upon request, through a switchboard. This common point became known as the telephone switching, central, or exchange office. The first such commercial telephone office, opened on January 28, 1878, in New Haven, Connecticut, served twenty-one telephones over eight open-wire lines called *subscriber loops*. Service was soon extended by interconnecting the switchboards in the telephone offices with additional wire lines which became known as *trunks*. Trunks interconnecting local offices were designated *exchange* trunks, while those interconnecting long distance offices were designated *toll* trunks.

During its early years, telephony was involved with transmitting only voice-frequency electrical signals over a single grounded wire line. The techniques first used to develop the outside wire plant for telephone circuits were borrowed from the older telegraph industry. Soon hundreds of wire lines, carried on crossarms which were mounted on wooden poles planted along streets and roadways began to appear in the towns and cities and along routes interconnecting metropolitan areas.

It was soon discovered that the single grounded wire line was not completely suitable for telephone communications because of such things as excessive electrical disturbances that were annoying to the users. This problem was solved with the development of the two-wire or *metallic* circuit. This type of circuit consisted of two closely paralleled wires, with one of the wires providing the current return path instead of returning the current through the earth.

Although the metallic circuit solved an interference problem, it presented the enormous problems of reconstructing practically the entire telephone plant and also doubling the already burdensome and oftentimes unsightly mass of wire lines. This seemingly overwhelming task was performed by the telephone industry during the period between 1890 and 1900.

Putting the wire pairs into cables served to remove some of the wire lines from view, but the problem of continually having to enlarge the outside wire plant to satisfy the increasing demand for more circuits still remained. A method of increasing the number of telephone circuits without having to add thousands of miles of more wire was sorely needed.

Multiplexing

Early in the development of telephone communications, it was found that a frequency range from about 300 to 2800 cps would convey speech with sufficient fidelity and clarity for commercial telephone service. (Modern telephone systems transmit speech sig-

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nals ranging from about 300 to 3400 cps.) However, since it was possible to transmit electrical waves of hundreds of thousands of cycles per second over wire lines, all the capabilities of the existing telephone circuits were not being used. This fact resulted in a search for a means of transmitting more than one telephone conversation simultaneously over a single pair of wires, a process known as *multiplexing*.

The underlying principles of multiplexing actually predate the invention of the telephone. Bell himself was experimenting with a type of multiplexing for telegraph systems at the time he conceived the idea of the telephone. Since electronic devices were not available to the early experimenters, they had to generate and select the alternating current *carriers* required for multiplexing by mechanical means. Initially, vibrating reeds, each with a different resonant frequency, were used for this purpose.

In these so-called *harmonic* telegraph systems, it was necessary to produce alternating current carriers in the order of only a few hundred cycles since the original signals were dc pulses. However, to multiplex telephone signals the carrier frequencies would have to be much higher. Carriers in the order of tens of thousands of cycles were considered to be necessary to preserve the characteristics of speech signals and to properly separate them electrically. But to produce frequencies of this higher order of magnitude, new and different techniques of generating alternating current were needed. Tuning forks, high-frequency commutator generators, and dc arc interruptors were among the first carrier producing devices considered for multiplex telephony.

Unfortunately, the early experimental types of telephone multiplexing were of little practical use. The development of successful multiplex systems had to await the arrival of the wireless or radio technology which occurred shortly before 1900. During the decade following 1900, a number of advances occurred which later helped to develop practical commercial telephone multiplex systems. Among these were the invention of the vacuum tube by Edison, the addition of a grid to the vacuum tube by DeForest, and the improvements in electrical wave filters.

In 1910, Major G. O. Squier, a United States Signal Corps officer, developed an experimental multiplex system which was operated over a short length of cable. This experiment restimulated interest in commercial multiplex telephony and led to extensive developmental effort by the Bell System

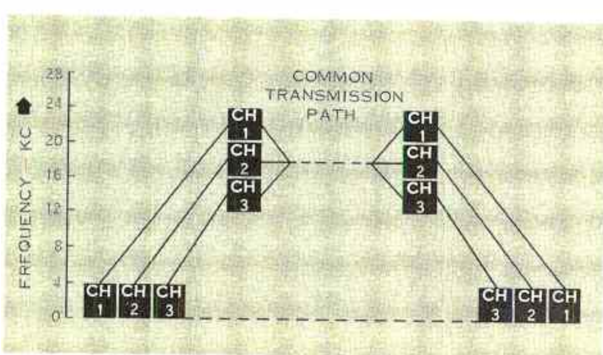

Figure 1. In frequency division multiplexing, low-frequency speech signals, ranging between 0 and 4 kc, are shifted to separate positions in a higher frequency range.

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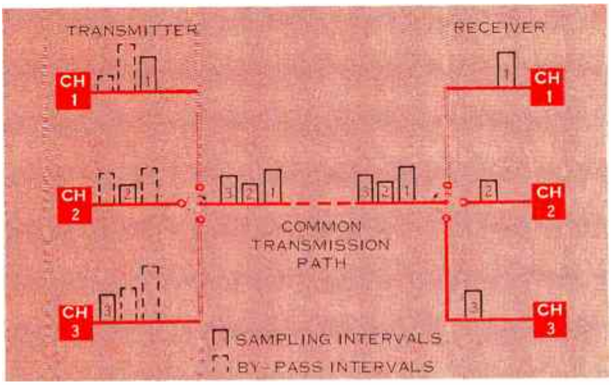
Figure 2. In time division multiplexing, speech signals are separated by briefly sampling each channel in a regular sequence.



—first by Western Electric and later by the Bell Telephone Laboratories.

It is interesting to examine some of the names that have been associated with the technique of multiplexing. The terms carrier current telephony and multiplex telephony appear often in early references, with other terms such as high frequency telephone, wired radio, and line radio receiving some notice. The term carrier telephony prevailed afterwards, but has been applied ordinarily only to wire systems, while the term multiplex telephony has been applied to radio systems. More recently, the term multiplex telephony has been used exclusively, regardless of the type of system to which it refers.

How It Works

In order to transmit two or more telephone signals simultaneously over the same circuit, the signals must be separated so that they do not interfere with each other. This can be done by separating them either in *frequency* or in *time*. Separating signals in frequency is known as frequency division multiplexing, whereas separating them in time is called time division multiplexing. The concepts of these two types of multiplexing are shown in Figures 1 and 2. Both methods were experimented with in the early stages of multiplex telegraphy. The vibrating reed technique, which used a different frequency for each telegraph channel, was an example of frequency division multiplexing. The most prevalent type of multiplexing used in the telephone industry has been frequency division.

Either frequency modulation or amplitude modulation may be used to transform speech signals to separate frequency bands, as required for frequency division multiplexing. Amplitude modulation is most commonly used. In this type of modulation, the resulting modulated wave consists of a carrier wave, an upper sideband wave, and a lower sideband wave. The two sideband waves are separated from the carrier wave by a frequency equal to the modulating speech signal. Each sideband wave includes all of the frequency components of the modulating speech signal. It soon became evident that only one sideband wave had to be transmitted. Therefore, the carrier wave and the other sideband wave could be suppressed, provided an equivalent carrier was available at the receiving end to demodulate the signal.

By using only one sideband, the energy required to transmit the signal is reduced considerably and the fre-

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quency band used is essentially half of that required if both sidebands and the carrier are transmitted. Thus, twice as many telephone channels can be obtained in the same multiplex frequency band. The technique of transmitting only one sideband, known as *single-sideband suppressed-carrier,* is used in most of the multiplex systems that have been developed for toll circuit use.

The basic components of a frequency division multiplex system, using single-sideband suppressed-carrier, are the modulators, demodulators, filters, and a source of carrier frequencies. Additional circuits are necessary to provide such things as power, signaling, and regulation. Figure 3 illustrates the use of the basic components in a simplified two-channel multiplex system.

In this system, speech signals received from the telephone transmitters associated with each channel pass through a low-pass filter which limits the upper end of the frequency range to about 4000 cps to conserve the frequency spectrum. Next, the signals are applied to a balanced modulator where they combine with a carrier received from an oscillator. (Note that the two carriers are different.) The carrier is suppressed in the modulator; therefore the output of the modulator contains only the upper and lower sidebands. The upper sideband is then attenuated in the bandpass filter leaving only the lower sideband for transmission. At this point, signals in channel one range between 6 and 10 kc, while signals in channel two range between 11 and 15 kc. Signals in both channels are now combined, amplified, and transmitted over the same transmission line.

At the receive terminal the combined signal appears at the input of two bandpass filters. The channel one bandpass filter passes only the 6 to 10 kc signals and rejects the 11 to 15 kc signals, while the channel two bandpass filter passes only the 11 to 15 kc signals while rejecting the 6 to 10 kc signals. Next, the signals in each channel are applied to a demodulator where they combine with a carrier of the same frequency as that used in the transmit terminal. The output of the demodulator is passed through the 4-kc low pass filter which attenuates the upper sidebands, leaving only the original speech signals to be transmitted to the telephone receiver.

Hence, this simplified multiplex circuit is able to electrically separate two speech signals so that they can be transmitted simultaneously over the same transmission line, without interfering with each other, and properly detected at the receiving end.

Early Commercial Systems

In 1914, a laboratory model of a complete multiplex telephone system was tested by the American Telephone and Telegraph Company on an open-wire line that extended from South Bend, Indiana to Toledo, Ohio. The results of this test proved the feasibility of multiplex telephony in commercial applications. Later, in 1918, the first commercial multiplex system began operating between Baltimore, Maryland and Pittsburgh, Pennsylvania.

The Bell System designated their original multiplex system as type A, thus beginning a succession of different systems with alphabet designations. The type A system provided four two-way channels for use over a single open-wire line, with the same carrier frequencies being used for each direction of transmission. This required the use of hybrid coils to separate the transmit and receive signals, a feature which later proved to be objectionable. In the next type of multiplex system, installed in 1920 and designated type B, three two-way channels were provided using different frequencies for each di-

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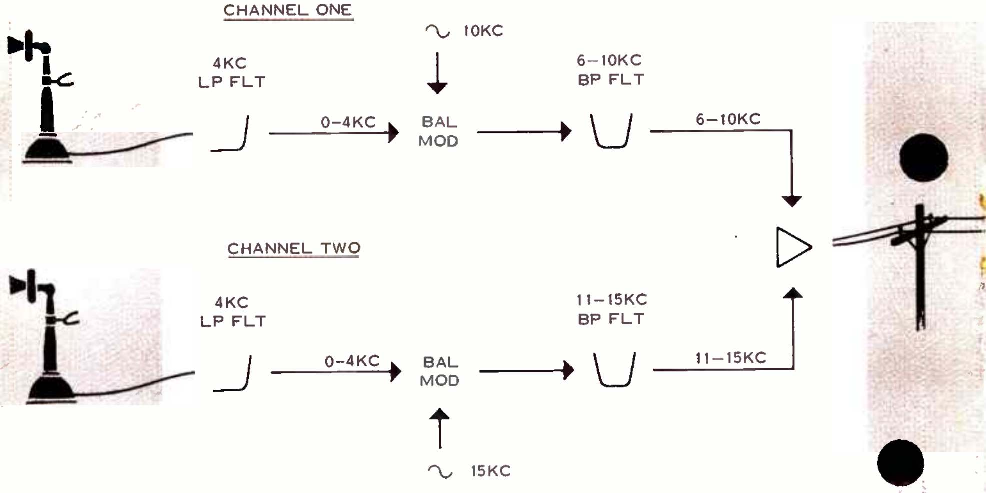
MULTIPLEX TERMINAL—TRANSMIT BRANCH



rection of transmission. This permitted the use of filters to separate the channels and the hybrid coils were no longer necessary. This technique of using different frequencies for each direction provided what is known as an *equivalent 4-wire* system.

Both the type A and B systems used amplitude modulation to superimpose the telephone signals onto the carriers. In the type A system, the carrier and one sideband were suppressed with only the other sideband being transmitted. However, in the type B system, one sideband was suppressed while the other sideband and the carrier were transmitted. When the type C system was developed in about 1925, it incorporated the best features of the two earlier systems. This system provided three channels using different frequencies for each direction of transmission, and transmitted only one sideband.

The initial developments in multiplexing were directed toward telegraphy, and the frequencies used for this service occupied the range below 10 kc. The frequency band from 10 to 30 kc, therefore, was used in the early telephone multiplex systems, limiting them to 3 or 4 voice channels. Although higher frequencies could have been used, at the time it was not considered practical because of the higher attenuation and crosstalk, and other factors associated with open-wire lines.

The type C multiplex system developed rapidly and was used extensively throughout the Bell System's long distance toll routes. By 1928, several transcontinental 3-channel multiplex systems were in operation along with many shorter systems between such points as Chicago and Pittsburgh, and San Francisco and Los Angeles.

Before the first commercial multiplex systems could be successfully used, it was necessary to measure and analyze the characteristics of the transmission medium to be used. Tests showed that the attenuation of open-wire and cable was a function of fre-

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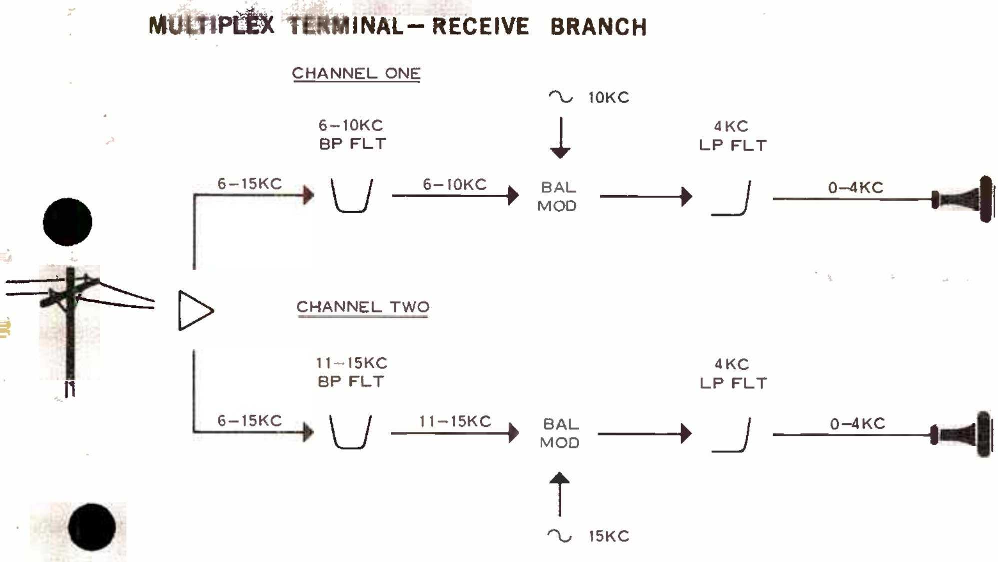

Figure 3. Simplified two-channel telephone multiplex system.

quency, and increased as the frequency was increased. The attenuation-frequency characteristics of open-wire pairs differed for different wire sizes and for different spacings of the wire pairs. The attenuation per unit length was much lower for open-wire pairs than for cable pairs under most conditions, but the open-wire pairs were more severely affected by changes in temperature and humidity, and by icing.

In the multiplex frequency band, the characteristic impedance of open-wire pairs varies somewhat with frequency, different wire gauges and spacing, but is generally considered to be about 600 ohms. However, for non-loaded toll cable the characteristic impedance is approximately 130 ohms.

Differences such as these greatly affected the design requirements of early multiplex equipment. In general, if a multiplex system was designed for one transmission medium, such as open-wire, it could not be readily adapted for use on a cable.

Soon, however, technical advances proceeded far enough to permit the development of twelve-channel multiplex systems designed to operate over non-loaded cables and open-wire lines. In the design of these systems, many new types of components were used and standardized so that they could be interchanged, thereby making multiplex systems more economical.

The first of these systems, designated type J, was designed for open-wire lines and had a line frequency range of about 36 to 140 kc. The frequency band from 36 to 84 kc was used for transmission in one direction and the frequency band from 92 to 140 kc was used for transmission in the opposite direction.

In addition, this system could be used with a type C system, operating in the 6 to 30 kc range, and a v-f cir-

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cuit to provide up to 16 telephone channels over one open-wire line.

The next 12-channel system, designated type K, was used on a transcontinental cable system and was put into service in 1938. This system used the frequency band from about 12 to 60 kc for transmission in both directions. This was done by using a different wire pair for each direction, thus establishing a *physical 4-wire* system.

The lower line frequency of the type K system was achieved using a new technique called *group modulation*. In the earlier systems, the multiplex line frequencies were accomplished by a single direct-modulation step. Group modulation, however, consists of using two or more steps of modulation to establish the line frequencies.

One of the most significant advantages of group modulation was that it provided a simplified means of interconnecting standard sub-groups of channels at line frequencies, a technique employed extensively in later multiplex systems.

Later Developments

Prior to World War II, multiplex systems were designed for operation over medium and long distance telephone routes. The development and installation of both the Western Electric 12-channel J open-wire and the 12-channel K cable systems established multiplexing as the method for deriving toll circuits over long distance routes. Not only was it possible to increase circuit capacity more economically, but the grade of circuit was improved.

Following the war, there was an unprecedented demand for more short, medium and long distance telephone circuits. At this same time, there was a shortage of materials for outside plant construction, and the costs of labor and materials were increasing.

To supply the telephone circuit requirements, new approaches to multiplexing were necessary, since its use prior to this time was considered economical only for long-haul circuits. For short- and medium-haul use, various multiplex systems were developed which were simple to install, operate and maintain, and which were competitive with voice-frequency circuits, even over very short distances.

These systems included the type N system and Lenkurt's type LN system, which provided 12 channels over two cable pairs, and the type O system and Lenkurt's type 45C system which provided four 4-channel groups or sixteen channels over an open-wire transmission line.

In a number of instances, the full channel capacity of a 12- or even a 3-channel system was not required. For this reason, *stackability* was desirable in multiplex equipment, and systems, such as the Lenkurt type 33A, were developed with a minimum of so-called common equipment. Thus, individual channel equipment could be added (stacked) later to meet future circuit needs.

The extreme flexibility afforded by stackable multiplex equipment, and its short-distance *prove-in* cost, permitted economical expansion and was a contributing factor to the use of multiplex systems for short- and medium-haul toll telephone circuits.

Once multiplexing had been firmly established as the standard method of deriving toll circuits, there was increasing pressure to reduce the physical size of the equipment. During and following World War II, a continuing effort was made to reduce the size of electronic components, and to add new devices—such as germanium and silicon diodes and transistors — which were small and required much less power than vacuum tubes. Lenkurt's type

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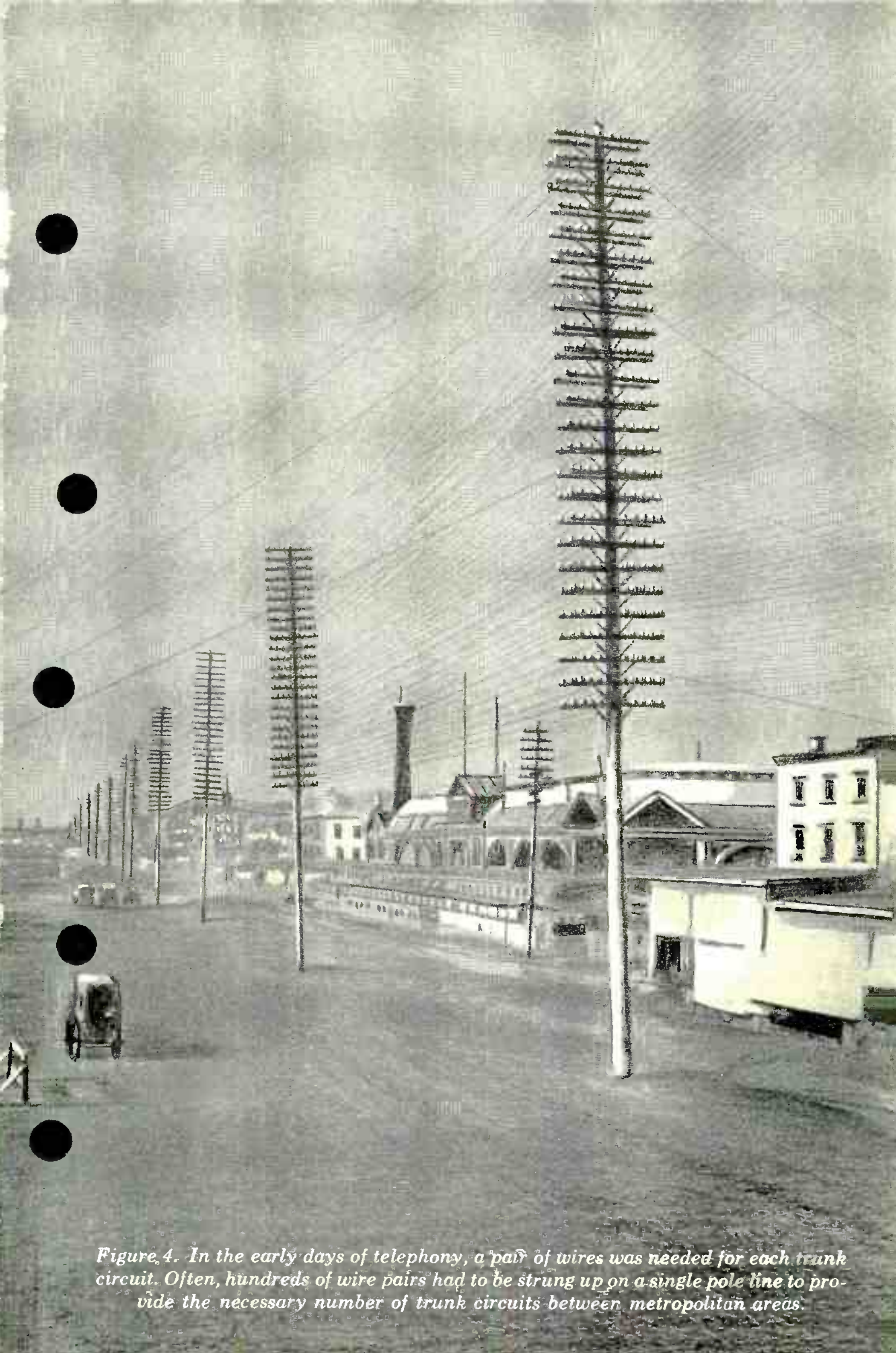

Figure 4. In the early days of telephony, a pair of wires was needed for each trunk circuit. Often, hundreds of wire pairs had to be strung up on a single pole line to provide the necessary number of trunk circuits between metropolitan areas.

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45A 12-channel system for open-wire lines, developed in 1952, was the first multiplex system designed to take advantage of miniaturization techniques and modular plug-in components. This system led to the development of a complete family of miniaturized multiplex systems for all transmission mediums.

Today's modern solid-state frequency division multiplex systems, such as the type N3 and Lenkurt's type 46B, designed to operate over standard types of toll cable, provide up to 24 channels with a line frequency ranging from about 36 to 264 kc. The line frequencies are different for each direction of transmission. These modern transistorized systems provide economical service for intertoll and toll-connecting trunks, and other medium- and short-haul applications.

The development of multiplex systems for short-haul applications led to its use in exchange trunks and subscriber circuits. These short-haul systerms provided a simple and economical means of providing up to 10 or 20 channels over a single open wire or cable pair. Subscriber multiplex proved to be particularly suitable in rural or sparsely-populated areas where one rural line could provide adequate service to as many as 50 homes. Exchange multiplex systems, such as the Lenkurt type 81A and type X, provided economical, high quality trunks for Extended Area Service and toll-connecting applications.

To compete with the cost of loaded cable pairs used for exchange trunks shorter than 10 miles, the Bell System developed a multiplex system significantly different from the conventional frequency division systems used in the past. This system, designated type T1, is a time-division multiplex system which uses pulse-code modulation to provide 24 telephone channels over an exchange trunk cable.

High Capacity Systems

Most of the development of multiplex systems prior to World War II was directed toward increasing the efficiency of open-wire and multipair cable facilities which provided almost all of the telephone circuits. However, the useable bandwidth of open-wire and multipair cable circuits limits the multiplexed channels to a rather small number. The capacity of open wire systems is limited to about 16 channels, while the capacity of multipair cable systems is about 24 channels. However, multiplex systems could be made to operate with much greater bandwidths than those provided by conventional wire systems. All that was needed was some wideband transmission medium.

Modern wideband transmission mediums are provided by coaxial cable and microwave radio facilities which are capable of handling hundreds of channels. In about 1948, the Bell System completed a transcontinental coaxial cable transmission facility, designated type L1, to be used for television as well as to provide a large number of telephone channels. The L1 facility is capable of handling up to 600 single-sideband suppressed-carrier frequency division multiplex telephone channels, or one television channel. Later, a higher capacity coaxial cable, designated type L3, was developed. This facility is capable of handling 1860 multiplex telephone channels, or one television channel and 600 multiplex telephone channels. The Bell System is presently working on the type L4 coaxial cable which will have a capacity of about 32,000 multiplex telephone channels.

In addition to the L-type coaxial cable transmission facilities, the Bell System has developed two long-haul microwave radio relay systems, designated type TD-2 and type TH. The

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TD-2 system, operating in the 4000 mc common-carrier band, has a capacity of 6000 multiplex channels, with a later version, the type TD-3, capable of handling up to 12,000 channels. The TH system, operating in the 6000 mc common-carrier band has a capacity of over 11,000 multiplex channels.

The single-sideband suppressed-carrier frequency division multiplex systems developed by the Bell System for use with the coaxial cable and microwave facilities have been designated type L. These systems are presently capable of providing up to 600 or up to 1860 multiplex telephone channels.

The type L multiplex systems combine the voice-frequency telephone circuits into 12-channel groups. A series of group modulation steps are then used to form up to fifty 12-channel groups (600 channels) into a baseband with a frequency range of 60 to 2788 kc, or up to 155 12-channel groups (1860 channels) into a baseband with a frequency range of 312 to 8284 kc. The Lenkurt type 46A multiplex system, developed for use with microwave radio, uses a modulation scheme compatible with that of the type L to multiplex up to 1200 channels.

These high channel capacity multiplex systems have provided an efficient and economical means of expanding the long-haul telephone plant to meet the great demand for more communications services. In addition, the development of these systems has resulted in considerable standardization, especially in group modulation schemes, thus permitting sub-groups of multiplex channels, derived from different systems, to be interconnected at multiplex frequency levels rather than at voice-frequency levels. This feature provides large savings in equipment costs and results in higher quality transmission. Also, these systems have greatly improved the performance standards and reliability of multiplex systems and have been instrumental in reducing the size of the equipment and in lowering the per-channel costs.

Conclusion

The telephone industry has grown at a significant pace since its beginning in 1876. This growth has been greatly effected by the development of multiplex systems which permit many speech signals to be transmitted simultaneously over a single open-wire, cable, or radio transmission facility. In recent years other industries have taken advantage of multiplexing to solve the problems of expanding their communications facilities. Among these other users are the railroads, pipeline companies, utilities, airlines, various government agencies, and the Armed Forces.

Today's modern multiplex systems are capable of handling not only speech signals, but many types of digital signals such as low and high speed data, which have added new dimensions to communications technology. In the near future, multiplexing will be providing channels for *waveguide* transmission facilities capable of handling perhaps 200,000 speech signals simultaneously. Perhaps further in the future, laser beams will be piped between major population centers carrying over one million multiplexed signals simultaneously.

Multiplexing has played a key role in promoting worldwide telephone communications, which has become essential to the efficiency and success of our society. The great communications systems that have emerged through the technological advances of multiplexing have indeed become a national asset.

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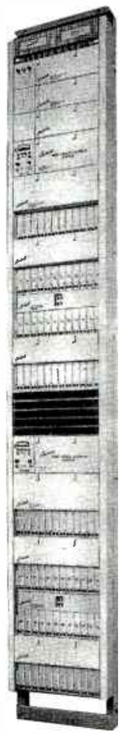
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