The T1 Carrier System

By K. E. FULTZ and D. B. PENICK

(Manuscript received May 11, 1965)

T1 carrier provides 24 voice channels by time division multiplexing and pulse code modulation (PCM). Each voice channel is sampled 8000 times a second and each sample is coded into a 7-digit binary word. Provision for signaling and synchronization raises the pulse repetition rate on the repeatered line to 1.544 $\times$ 10^6 pulse positions per second. The bipolar pulse train out of the terminals is transmitted over pulp, paper or plastic insulated paired cables by the use of regenerative repeaters. For 22-gauge cable pairs, repeaters are normally located at 6000-foot intervals.

The system has been designed for low cost and is being widely applied on many trunks interconnecting switching units within metropolitan areas. Western Electric Company manufacture of T1 began in 1962 and about 100,000 channels are now in service throughout the Bell System.

I. INTRODUCTION

The rapid expansion in the telephone network that has occurred since 1950 has stimulated a thorough investigation of methods for reducing the cost of additional trunk facilities. The desire to improve the quality of telephone service has given additional emphasis to studies of improved trunking arrangements. One way to obtain additional trunks for growth is to increase the utilization of existing conductors by using them to transmit more than one voice signal. For such an arrangement to be economical, the savings from the more efficient use of the transmission line must more than offset the cost of the terminal equipment required to multiplex a number of voice channels. On trunks between cities, carrier systems (systems transmitting a number of voice channels) have been economical for many years. The lower terminal costs achieved in the T1 carrier system

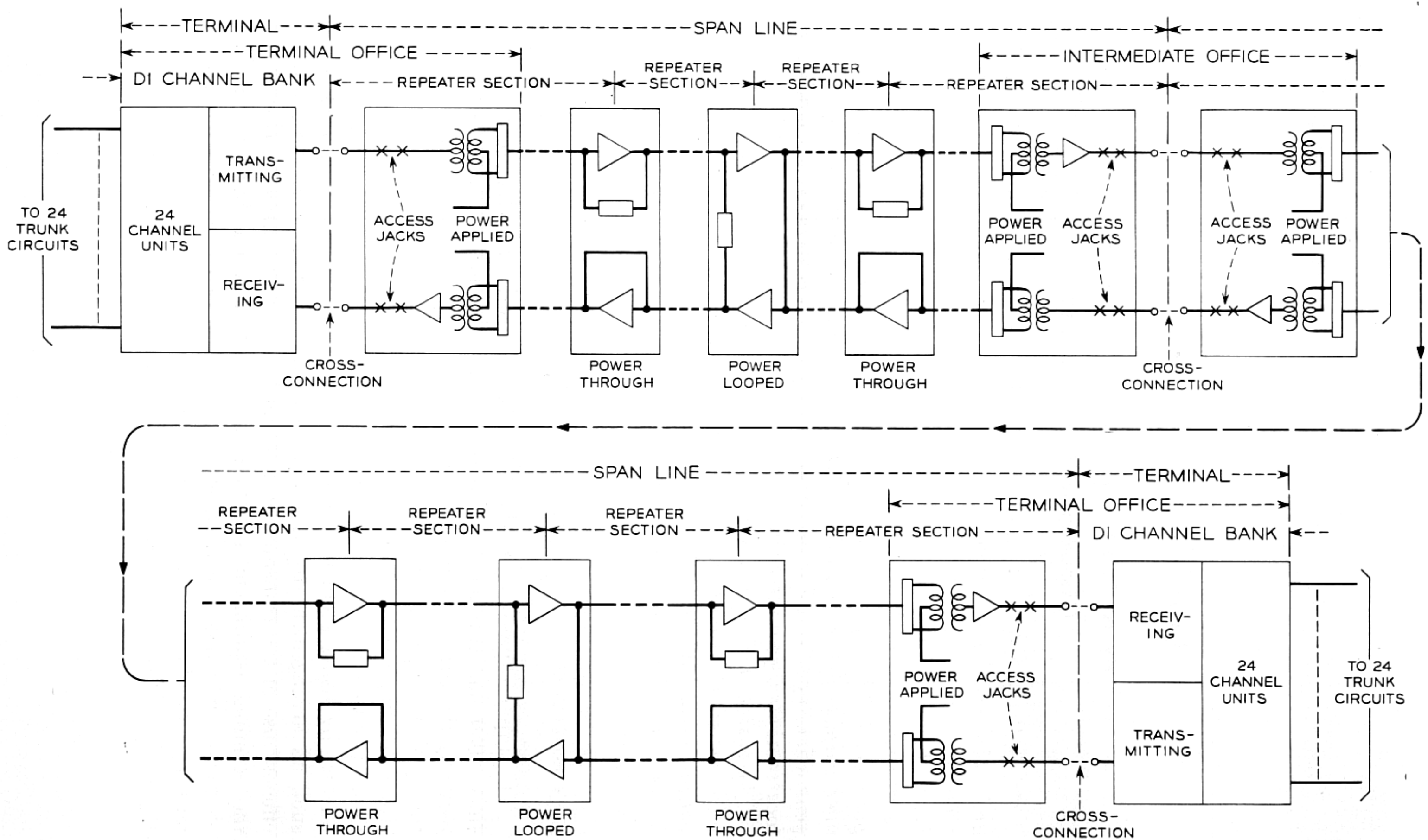

Fig. 1 — Typical T1 carrier system.

have made carrier systems economically attractive for the longer trunks between local offices within a city. In a large number of situations the T1 carrier system will prove-in over voice frequency circuits for distances longer than 10 to 12 miles. Satisfactory performance is achieved over lengths up to 50 miles, and the performance over longer lengths is being evaluated.

A major contributor to the low terminal costs in T1 is the economy with which the signaling information required to control the switching equipment can be transmitted in a digital system. In most carrier systems the digital signaling information is converted into analog tones for transmission. In a digital system the signaling information can be added directly to the coded speech samples with the saving in digital-to-analog conversion of the signaling information. Additional economies are achieved by an instantaneous compandor shared by a number of channels rather than individual channel syllabic compandors as used in some carrier systems.

The T1 carrier system now being manufactured by the Western Electric Company is a refinement of the experimental PCM system described in the January, 1962, issue of this Journal.[1-5] The basic system plan and the fundamental circuit approaches remain unchanged.

It is convenient to consider a PCM system as being composed of two parts — a PCM terminal and a digital transmission line. For regular telephone trunks, the PCM terminal for the T1 system is the D1 channel bank. The D1 channel bank combines 24 voice channels in a time division multiplex and encodes them in a scale of 127 quantized amplitude levels (63 steps positive and 63 steps negative from zero) into a single pulse train. In the receiving direction, it reconstructs the analog speech signals from the incoming pulse stream. Other terminal arrangements are being provided which prepare wideband data signals for transmission over T1 repeatered lines. These terminals are discussed in a companion paper.[6]

The T1 repeatered line consists of cable pairs equipped with regenerative repeaters at appropriate spacings. At the end offices, and at intermediate offices along the route, each repeatered line passes through an office repeater which provides a regenerator for the incoming signal, powering circuits for the line repeaters, access jacks for patching, monitoring jacks, and cross-connection points for route flexibility. A block schematic of a typical T1 carrier system is shown in Fig. 1.

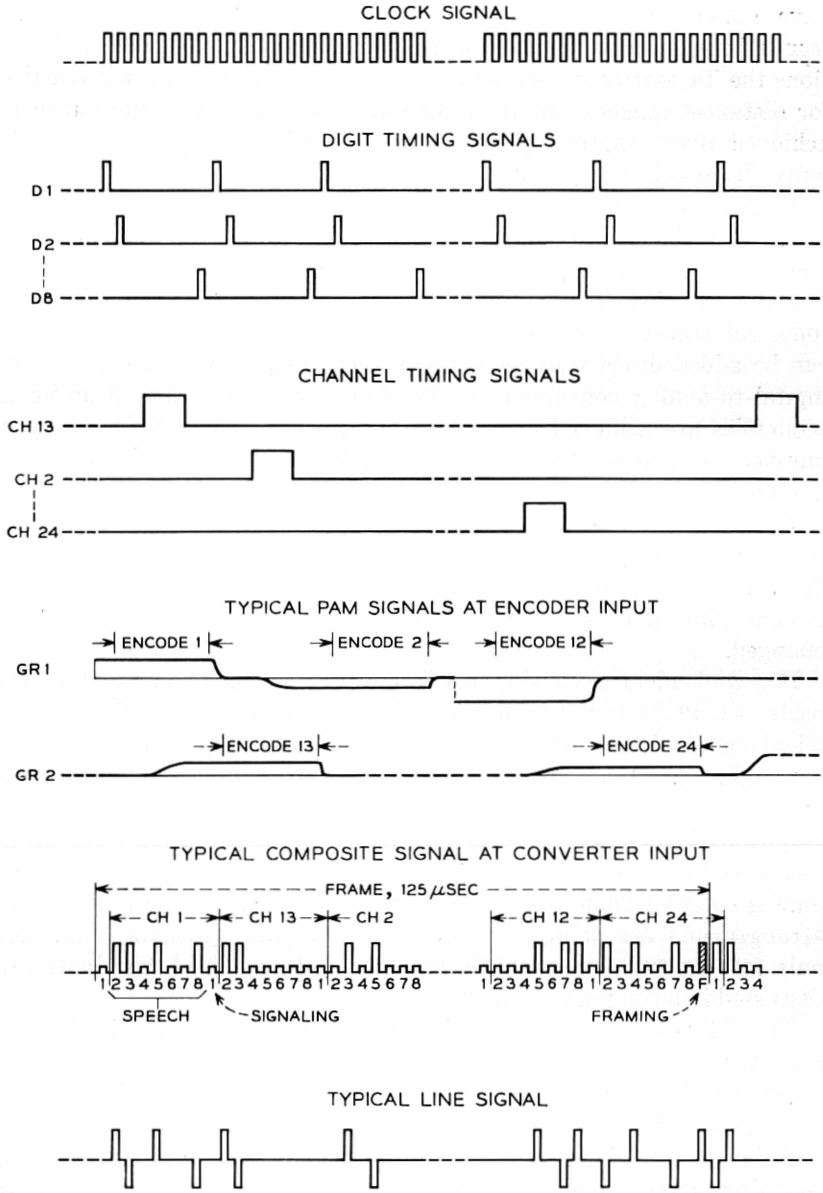

Fig. 2 — D1 bank pulse trains used in multiplexing and encoding.

II. D1 CHANNEL BANKS

2.1 *Group and Channel Circuits*

Most of the transmission functions in a D1 channel bank are performed in a block of circuits shared by a number of voice channels. These group circuits may be divided into two sections — transmitting and receiving. The transmitting group equipment samples the incoming voice signals for each channel, multiplexes the sample in time division, compresses and encodes the samples, combines the encoded sample with signaling information, and prepares the pulse train for transmission over the line. Fig. 2 shows the more important pulse trains involved in this process. The receiving group equipment accepts the incoming pulse stream, separates the signaling information from the coded samples, decodes and expands the speech samples, demultiplexes them, and reconstructs the voice signal. Thus, the group equipment provides 24 voice channels plus 24 signaling channels in each direction. Each signaling channel has a theoretical capacity of 8 kilobits/second. In some situations — revertive pulsing and foreign exchange lines — additional signaling capability is obtained by using the least significant* speech digit when speech would not usually be present.

The channel units shown in Fig. 1 are used to match the voice and signaling paths provided by the group equipment to the requirements of the individual switching circuits to which each channel is connected.

A block schematic of the group circuits is shown in Fig. 3. Consider first the transmitting direction shown in the upper half of the schematic. The transmission circuits in heavy lines come in at the left side from 24 plug-in channel units not shown. Six channels connect to each of four transmitting gate and filter plug-in units. Each gate and filter unit contains six low-pass filters and six sampling gates. The four gate and filter units are arranged in two pairs, a pair for each of two 12-channel groups. The sampling times of the two groups are interleaved so that group 1 channels are sampled at odd-numbered sampling times and group 2 channels at even-numbered times. Thus the channels appear in the PAM (pulse amplitude modulated) pulse train in the order: 1, 13, 2, 14, $\cdots$ 11, 23, 12, 24, 1, 13, 2, 14, $\cdots$.

The common output of each group of twelve gates connects to its own compressor, which reduces a wide range of input amplitudes to a

* The seventh digit of a seven-digit binary code is the least significant since it affects the coded amplitude by only 1 part in 128. The first digit affects the amplitude by 64 parts in 128, the second by 32 parts, etc.

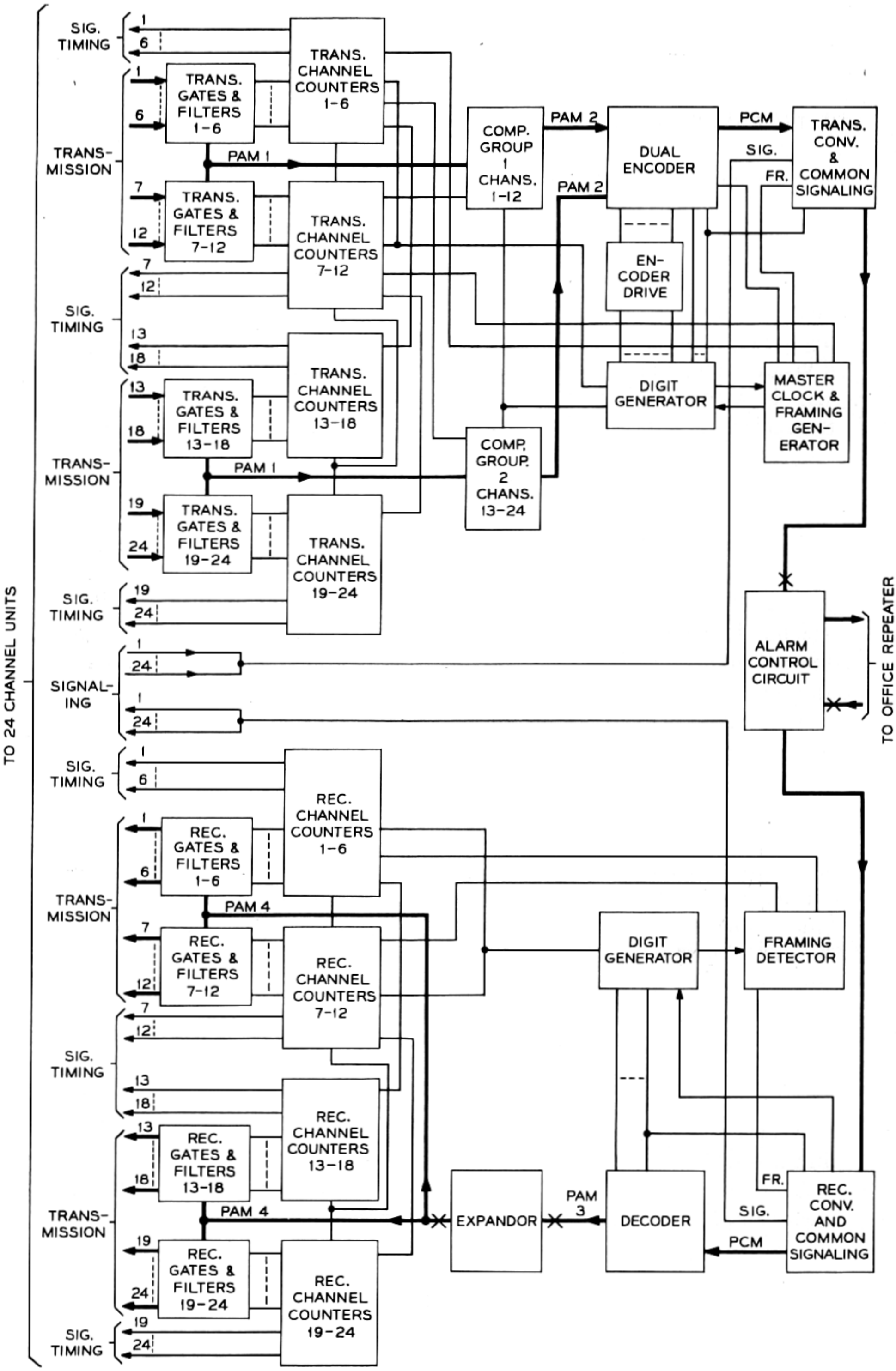

Fig. 3 — D1 bank group circuits.

smaller range of output amplitudes in an almost logarithmic relationship. An input range of approximately 60 decibels (1000-to-1 amplitude ratio) is reduced to an output range of 63-to-1 amplitude ratio in a modified logarithmic-to-linear conversion, so that the output variation in volts amplitude is approximately proportional to the input variation in decibels over most of the range. The two compressor outputs are connected to the dual encoder. Its two summing amplifiers and comparison networks, under the logic control of the encoder drive unit, encode the two pulse trains alternately into a single stream of PCM pulses.

This unipolar PCM signal, occupying seven of the eight pulse positions assigned to each channel sample, is one of three signals fed into the transmitting converter and common signaling unit. A second signal is processed by the common signaling portion of this unit, which accepts a signaling pulse from the scanning gate of each of the 24 channel units in turn, reshapes each one, and times it to interleave with the PCM pulses in the unipolar train. A third signal entering this unit is a framing signal from the framing generator, occupying a single pulse position per frame. These three signals, added together in the converter, form a combined pulse train of 193 pulse positions per frame. This number, multiplied by the frame repetition rate of 8000 per second, yields the basic pulse repetition rate of 1,544,000 per second.

As a final step in the converter processing before the pulse train is sent out over the repeatered line, each pulse is regenerated and alternate pulses, when they appear, are inverted to form a bipolar signal. This signal, then, is transmitted to the line by way of the alarm control unit located on the receiving shelf.

Timing for the signal processing circuits is derived from a crystal-controlled oscillator, a part of the master clock. The oscillator output, shaped into square-topped pulses, each occupying about one half of its allotted time interval, drives a digit generator which is basically a ring counter composed of blocking oscillators. Each of eight stages sends out one of eight successive digits on a lead per digit for use as required in encoding and other timing functions. A second lead per digit is also provided for digit pulses of opposite polarity. A ninth stage provides a ninth pulse at the end of each frame for framing control in conjunction with the framing generator included in the master clock unit.

Digit pulses, in turn, drive a set of channel counters which provide timing for both voice sampling gates and signaling scanning gates. As in the case of the digit generator, the counter stages are blocking oscillators. They are turned on in rotation by one digit pulse and turned off by another. Each counter unit accommodates six stages, so that for a completely equipped D1 bank, four units are required. The circuits are arranged, however, so that the two units associated with the group 1 channels form a 12-stage ring counter which is self-sustaining. The two units for the group 2 channels are separately driven from the ring, and may be omitted in a partially equipped bank without disturbing the group 1 operation. Some of the functions of the group 1 counters are not required for group 2, so a separate network code, simpler and less expensive, is provided for group 2 only. The group 1 counter will also operate in group 2 positions, and therefore is conveniently used as a spare.

The interconnections of the plug-in units which make up the receiving portion of the D1 bank are shown in the lower half of Fig. 3. The combined pulse train from the distant terminal, transmitted over the repeatered line and through the local office repeater, is received by the alarm control circuit at the right side of the schematic. Reduced by a pad to a convenient amplitude, it is sent into the receiving converter and common signaling unit. At this point the pulse train is reconverted to unipolar form, regenerated, and impressed simultaneously on framing, signaling, and PCM circuits. These circuits time-select appropriate pulses from the combined pulse train for further processing.

The PCM circuit connects to the decoder, which scans the seven pulse positions allocated to each sample and synthesizes from the code the compressed sample amplitude for the corresponding PAM pulse. The resulting train of PAM pulses passes through the expandor, which restores the original, uncompressed amplitudes and transmits them to the bank of receiving gates. The gates, operating one at a time in rotation, route each PAM pulse through an individual low-pass filter to the receiving branch of its associated channel unit.

The signaling pulse associated with each seven-pulse code at the converter output is selected by the common signaling timing, is amplified to a suitable pulse amplitude and duration, and is passed to the bank of receiving signaling gates in the channel units. The gate in the appropriate channel unit transmits the individual pulse in each frame to its corresponding amplification and reconstruction circuit, also in the channel unit, and reproduces the signaling state corresponding to that which was scanned at the distant terminal for that channel.

Timing for the receiving circuits is very similar to that for the transmitting circuits except that the clock signal, instead of originating in a crystal-controlled oscillator, is derived from the incoming pulse train itself acting on a tuned circuit resonant at the expected bit rate. The dissipation of the tuned circuit is low enough so that oscillation of the slave clock is maintained over moderately long blank periods in the incoming pulse train. The clock signal, produced in the converter as part of the pulse regeneration process, also drives a digit generator, a duplicate of the one in the transmitting circuit.

Digit pulses, as in the transmitting circuit, drive channel counters which time both the transmission gates and signaling receiving gates associated with the individual channels. Also, as in the transmitting circuit, a framing pulse is produced at the end of each frame as determined by the state of the channel counters. Thus, the bit rate, digit pulse rate, channel rate, and frame rate are identical with those in the transmitting circuit. Synchronism, once achieved, is therefore maintained indefinitely as long as the incoming pulse train is not interrupted.

Restoration of phase synchronism, or framing, after an interruption is accomplished under the control of the framing detector. This unit receives the framing signal generated in the receiving timing circuits and compares it with the corresponding signal in the incoming pulse train. The framing signal is a fixed pattern consisting of alternating ones and zeros in every 193rd pulse position, a pattern seldom duplicated for more than two or three frame intervals at a time in any other pulse position. When the framing detector comparison indicates a number of rapidly occurring differences between the received pattern and the local framing signal, a logic circuit starts a hunting action by inserting an additional pulse per frame in the local signal, thus comparing the local framing signal with each pulse position in turn of the incoming signal until the framing position is reached. When the two patterns match, the system is in frame and the hunting action ceases.

As noted earlier, the function of the channel units is to match the 24 sets of voice and signaling paths to the 24 individual trunk circuits to which they are connected at each end. A channel unit may provide a 4-wire terminating set and signaling converters for connecting conventional dc signaling to the carrier derived signaling channels or may connect the voice paths directly to a 4-wire trunk circuit. Instead of making numerous cross-connections at intermediate distribution frames to interconnect the specific terminating equipment required to implement a circuit order, a channel unit with the appropriate functions is selected and inserted in the carrier bay.

The use of channel units solely for matching the conditions on the

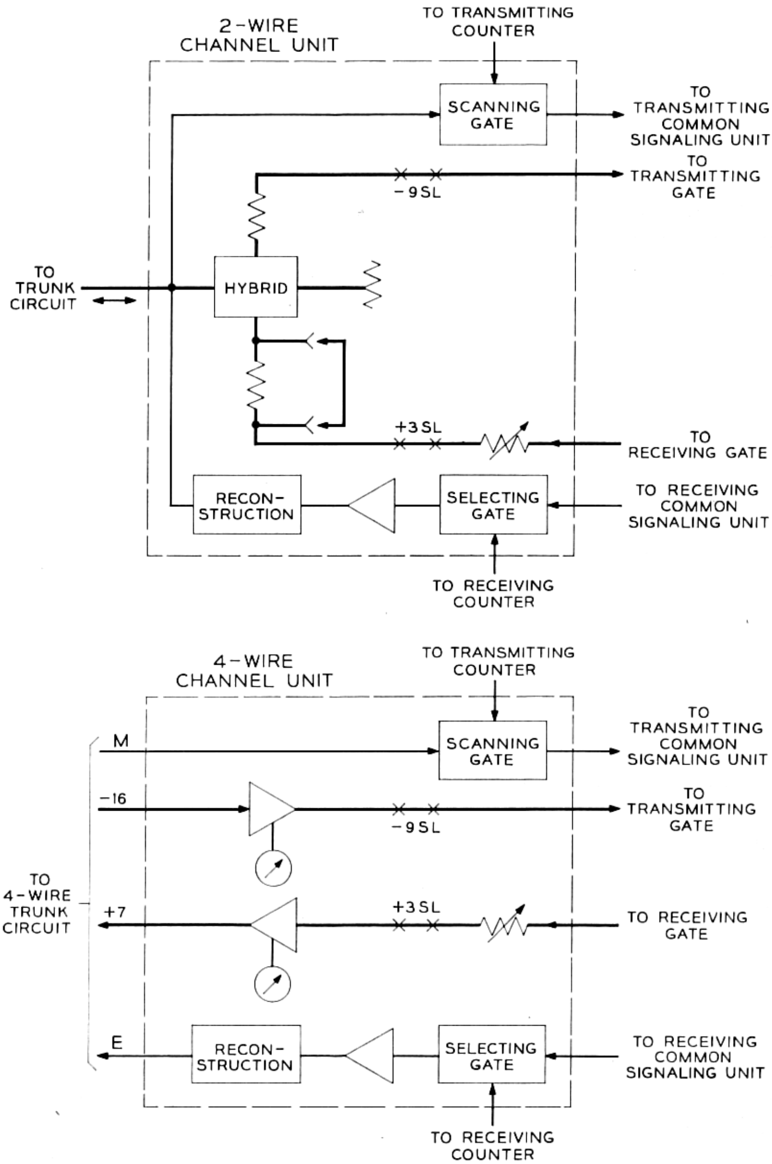

Fig. 4 — Typical D1 bank channel circuits.

voice frequency inputs to the carrier channels is quite different from the function of channel units in most frequency division multiplex (FDM) carrier systems. FDM channel units usually include filters which are different for each channel in a system. There is no difference in the T1 carrier channel units with respect to their position in the time division cycle. The different types of channel units required to meet local circuit needs may be intermixed in a channel bank in any order.

The two major types of channel units are the two-wire and the four-wire types as shown in the block schematic of Fig. 4. The two-wire channel units include a hybrid coil used as a terminating set. They also include transmitting and receiving access jacks for lineup use, a level adjusting pad, and two fixed pads, one of which may be strapped out. These elements constitute the transmission circuit and are the same for all two-wire units.

The four-wire unit transmission circuit does not require a hybrid coil, but provides an amplifier and an access jack in each direction of transmission, as well as a level adjusting pad in the receiving direction. The amplifier gains are adjustable over a range of about 1.5 db each for overcoming office wiring losses and are arranged to provide the nominal levels of −16 db and +7 db respectively, within 0.2 db, at the channel unit when the gain adjustments are turned to minimum.

The basic signaling functions for all channel units are the same. At the transmitting end in each direction, a scanning gate monitors the signaling state presented to it and converts it to a stream of corresponding signaling pulses, off or on, for transmission to the receiving end. There, a selecting gate recognizes the pulses, amplifies each one, and operates a reconstruction circuit which produces the signaling state corresponding to that scanned at the transmitting end. The differences between channel units lie in the methods required to translate the varying signaling states to pulses and reconstruct them again from pulses.

The most commonly used types of trunks in the exchange plant, which T1 carrier is designed to provide, are one-way trunks with either dial pulse or revertive pulse signaling and reverse battery supervision. The dial pulse signaling functions are quite straightforward. Loop closures are transmitted in the originating-to-terminating direction and battery reversals in the terminating-to-originating direction. In both directions, the digit 1 position in the train of eight pulses per channel is used to transmit the required information. Since the scanning gate requirements and relay requirements are quite different for the two directions, it is convenient and economical to use different designs for the originating and terminating channel units.

The same design basis applies also for revertive pulse signaling. Here the loop closures and loop opens in the originating-to-terminating direction represent start and stop signals, respectively. In the terminating-to-originating direction, it is necessary to transmit both battery reversals for supervision, and loop closures for the revertive ground pulse during dialing periods. The second signal in this direction requires an additional scanning gate in the terminating unit and an additional selecting gate, amplifier, and reconstruction circuit in the originating unit.

It also requires another signaling state, provided by "borrowing" another digit in addition to the digit 1 normally provided. Since the added digit is not needed for signaling during the normal talking period, digit 8, the least significant of the 7 PCM digits, is used and is returned to the PCM function as soon as the called customer returns the normal supervisory signal. One result of this arrangement is that operator connections, or others which do not return supervision, will have only 6 PCM digits available for transmission. These added functions, of course, require two additional channel unit designs, one each for originating and terminating units.

A demand for foreign exchange trunk service over T1 has inspired the design of two more channel units, which are now available. They connect the line circuits at the serving office end and customer end, respectively. All three available signaling states are used in both directions of transmission. In the serving office-to-customer direction, a tip ground signal and a ringing signal are transmitted. In the customer-to-serving office direction, a loop closure signal and a ring ground signal are transmitted.

The four-wire channel unit is designed for symmetrical two-way trunks with identical signaling in the two directions. In either direction, ground and battery on the M lead at the transmitting end become open and ground, respectively, on the E lead at the receiving end. Thus, the same design of channel unit is used at both ends of such trunks.

The four-wire channel unit may also be used with existing trunk converter circuits to connect to any of a large number of other types of trunks for which specific channel units have not been provided.

It is also feasible to use a four-wire channel unit at one end of a T1 carrier circuit and a two-wire unit at the other end to avoid the use of a converter, which in some cases would otherwise be required.

2.2 *Bay*

The basic channel bank bay is 11 feet, 6 inches high and 23 inches wide. It mounts three D1 banks, each associated with one 24-channel system, with their associated power supplies. Fig. 5 is a photograph of a typical installation showing an unequipped bay and a working bay filled with plug-in units. The unequipped bay consists of a supporting framework, die-cast metal shelves for the plug-in units, multipin connectors, and terminal strips. The terminal strips and connectors, including special screw connectors for hanger-mounted power supply panels, are prewired and fully tested at the factory. A 9-foot bay mounting two D1 banks and a 7-foot double bay mounting three D1 banks are also available.

The cost of these unequipped bays is comparable to the cost of engineering and installing them. Since the engineering and installation costs per bay are lower when a number of bays are installed at a time, it is economical to install more bays than are required immediately. At installation, the voice frequency connections are wired to the distributing frame, the 1.544-megabit digital leads are extended to a 1.544-megabit cross-connect field on either the office repeater bay or a separate bay, and the −48 volt power leads are connected to the battery supply. When traffic requirements materialize, the more expensive plug-in units may be inserted in the carrier bays. At that time, office personnel will cross-connect the additional carrier-derived voice channels to switching trunk circuits and cross-connect the outgoing and incoming digital circuits to the appropriate repeatered line.

2.3 *Plug-In Units*

The active circuits are of three general classes: power supply, group timing and processing circuits, and channel units. The power supply consists of a dc-to-dc converter and regulators. It provides well regulated voltages of −24 v, +24 v, −42 v and +48 v from the −48-volt office battery. In general, the lower voltages supply the digital circuits and the higher voltages supply the dc stabilized analog circuits. The dc-to-dc converter and the analog voltage regulators serve all three D1 banks on a bay, but each D1 bank has its individual regulator for the digital circuit voltages.

The group equipment plug-in units are eight inches high and eight inches deep. One shelf, mounting fifteen units, is devoted to transmitting and a second shelf, mounting fourteen units, is used for receiving. Thus the group equipment for one D1 bank consists of 29 plug-in units mounted in about 16 inches of vertical bay space.

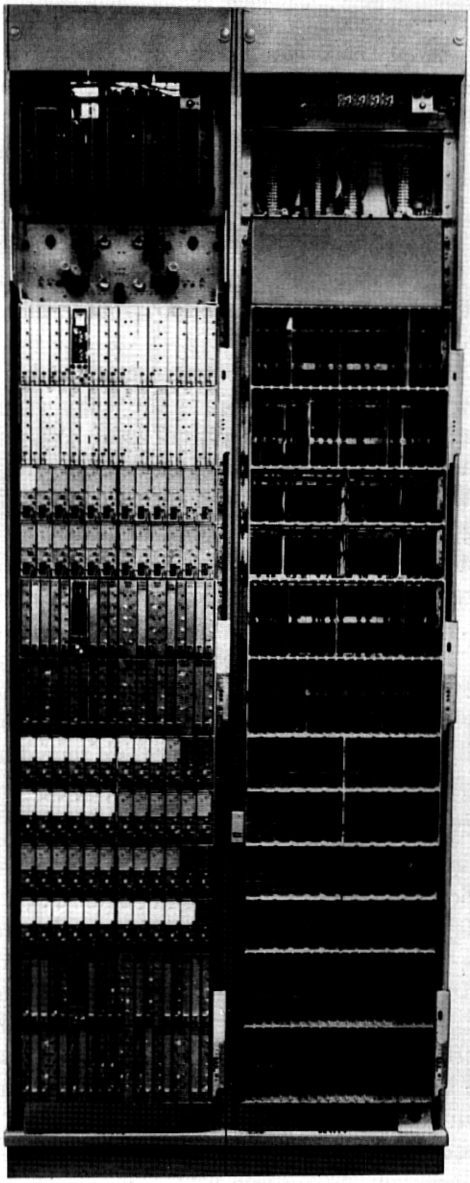

Fig. 5 — Typical D1 bank installation.

The 24 channel units in each D1 bank are mounted in two rows of twelve. Each channel unit is about 6 inches high, 8 inches deep and 1¾ inches wide. A photograph of a set of group and channel plug-in units in place for one D1 bank is shown in Fig. 6. Three typical plug-in units are shown in Fig. 7.

While the advantages of compactness are recognized, no major compromises were made in the equipment design for extreme miniaturization. Emphasis was placed instead on high reliability, design for

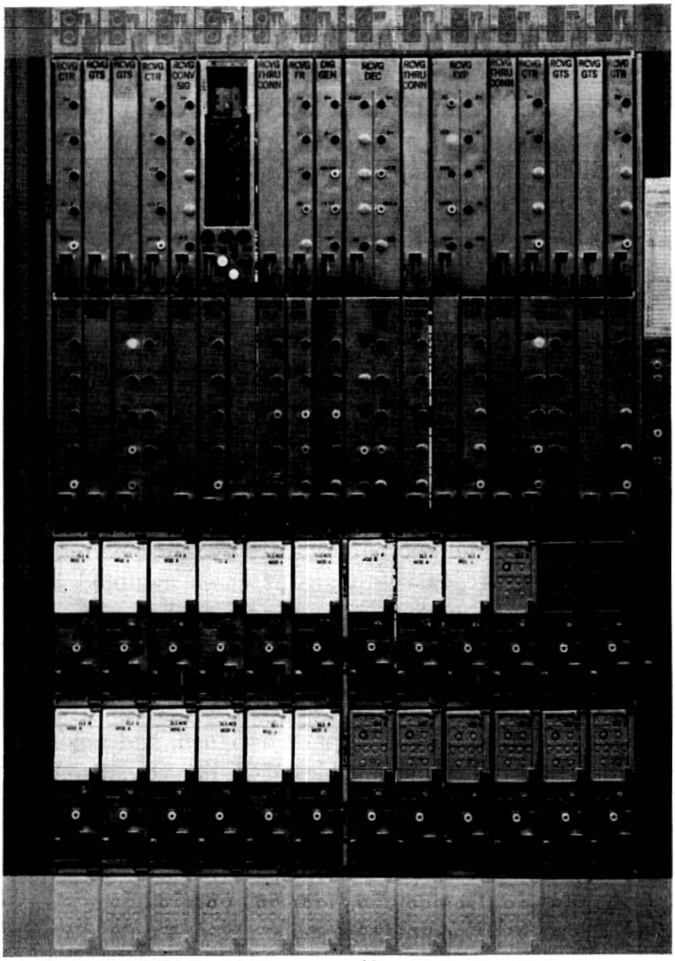

Fig. 6 — Group and channel units in place for one D1 bank.

mechanized assembly, mass soldering capability, and accessibility for inspection and repair. The book-case arrangement of units, however, uses the available volume efficiently.

One of the early choices in the arrangement of circuits and equipment was the consideration and rejection of the use of larger numbers of small, universal circuit packages such as gates, flip-flops, and blocking oscillators. The prospect of high production rates for relatively few types of basic modules is economically attractive. Analysis of the circuits showed, however, that each type of circuit block required so many variations for different points of application that the economies inherent in high production rate could not be realized. In the current design, the circuit packages are made large enough to include all of the specialized circuit blocks required to perform a larger circuit function. A digit generator, for example, uses nine similar blocking oscillators which operate in rotation. Several variations in these stages, however, would preclude using nine identical blocking oscillator packages unless each included all of the variations.

III. REPEATERED LINE

3.1 *Span Complements*

The digital transmission line, or repeatered line, extends from terminal to terminal of a system, and consists of two cable pairs equipped with repeaters for the two directions of transmission. The administrative line unit is a span line extending between office repeaters. A span line is composed of a number of repeater sections permanently connected in tandem at repeater apparatus cases mounted in manholes or on poles along the span. A span is defined[7] as the group of span lines which extend between two office repeater points. The repeatered line of the typical system of Fig. 1 is composed of two span lines, each of which happens to have four repeater sections.

Span lines are engineered, cable pairs assigned, and repeater mounting arrangements provided in multiples of 25-line complements. In one-cable installations (both directions of transmission in the same cable sheath), each set of apparatus cases along the cable serves a 25-line complement. In two-cable operation (the two directions of transmission in separate cable sheaths), two sets of apparatus cases, one for each cable, serve two 25-line complements. A single shop-wired repeater bay provides mounting arrangements for office repeaters for one end of three 25-line complements.

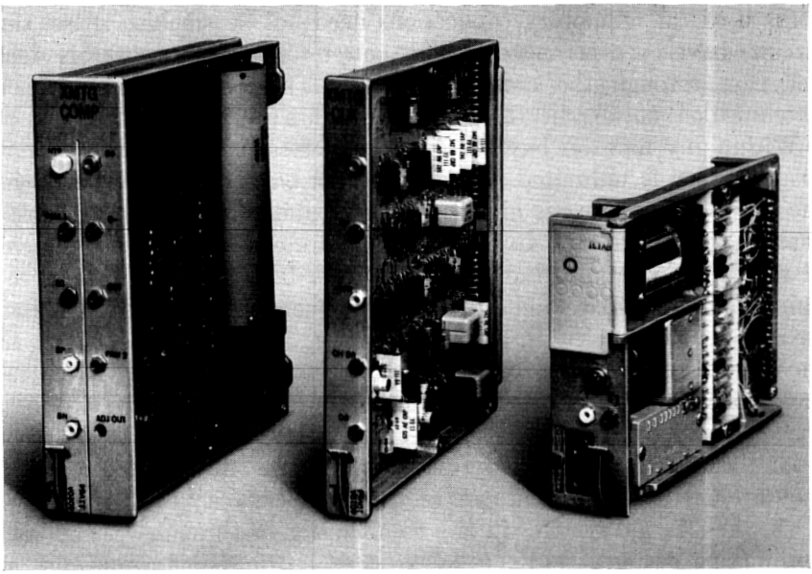

Fig. 7 — Typical D1 bank plug-in units.

Messrs. Crater and Cravis[7] have discussed the factors involved in the selection of cable sheaths and the spacing of apparatus cases.

The functions of the office repeater are to feed power to the repeatered line, regenerate the low-level incoming signal, provide jack access to the lines for patching and monitoring, and to provide a cross-connect field for connecting span lines to other span lines or to terminals.

3.2 *Cross-Connection Between Spans*

A cross-connect field is an integral part of the office repeater mountings. The 1.544-megabit connections to D1 banks and data terminals appear on this cross-connect field as well as the incoming and outgoing repeatered lines. All of these access points are designed to operate at the same signal level — namely, 3-volt pulses. To deliver a 3-volt pulse at the cross-connect field, D1 banks produce a 6-volt pulse which is padded down by 6 db in the combination of an equalizer on the D1 bank bay plus the cable from the D1 bank bay to the cross-connect field on the office repeater bay. With no level difference involved, all cross-connections can be made with unshielded twisted pair with no requirement for spacing or segregation. Similarly, patch cords used for temporary connections need not be shielded. Also, the circuits have been arranged so that power for the line repeaters does not pass through the cross-connections. Thus, cross-connection or patching does not disturb the line power within a span.

Within any repeater bay, flexibility for cross-connecting any circuit to any other is unlimited. Where repeater bays are side by side in the same lineup, there is also complete flexibility for inter-bay cross-connections. Where repeater bays are separated, judicious assignment of routes can minimize the number of inter-bay cross-connections required, and a limited number of such cross-connections can be handled by means of tie cables. In general, however, flexibility is restricted. In such cases, complete flexibility can be gained by installing a central cross-connect field. A field is available which mounts in two bay spaces, has all terminals for cross-connecting placed less than 7 feet from the floor, and can be provided with demountable doors where they are desired for appearance reasons. The capacity of a single unit of this field is 450 systems in any combination of through systems and terminating systems, and can be extended indefinitely in multiples of 450 systems by adding more units side by side. All office repeaters, data terminals, and D1 Banks to be cross-connected are wired to this field. The only present restriction to the use of this or any other cross-connecting method is that for through systems, the total length of office wiring between the two interconnected span terminating repeaters may not exceed 150 feet.

3.3 *Line Repeaters*

The design of an experimental line repeater and the engineering of the repeatered line have been described in earlier issues of this Journal.[2, 7] The line repeater developed for manufacture is substantially the same as the experimental unit with some refinements. Fig. 8(a) shows the configuration of a typical repeater and Fig. 8(b) is a block schematic of a regenerator. Each repeater contains two regenerators, mountings for two line build-out networks, a powering circuit to provide a regulated voltage to operate the active transmission circuits, and four option screws, L, L, and T, T, used in pairs for either looping the line power or connecting it through as required.

Each regenerator contains a preamplifier, a threshold bias circuit, a clock rectifier, a clock signal processing circuit, timing gates, and a pulse generator. The preamplifier amplifies and equalizes the incoming signal, reshaping each pulse to reduce its dispersion into adjacent time slots. Its output drives not only the regenerating circuit but also the

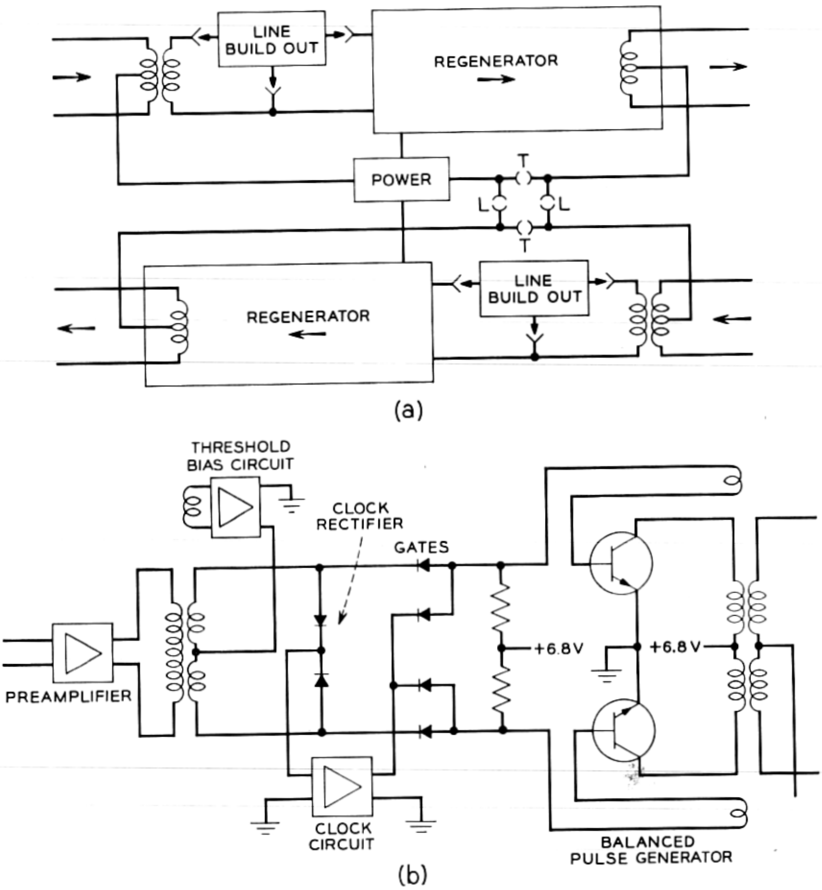

Fig. 8 — (a) 201A repeater configuration; (b) repeater regenerator.

clock circuit and the threshold bias circuit. The threshold bias circuit sets the decision level which determines for each time slot whether or not a pulse is to be regenerated, and optimizes it over a moderate range of variation of incoming signal level. The clock rectifier converts the incoming bipolar signal into a unipolar pulse train which contains a strong component of energy at the original repetition rate of 1.544 megacycles.* This 1.544-megacycle component is selected by a tuned

* In order to limit the time interval during which the clock must sustain the pulse repetition rate, the all-zeroes code of the transmitted signal is not used. This reduces the number of available codes from 128 to 127 and assures that in each eight-digit word there will be at least one pulse.

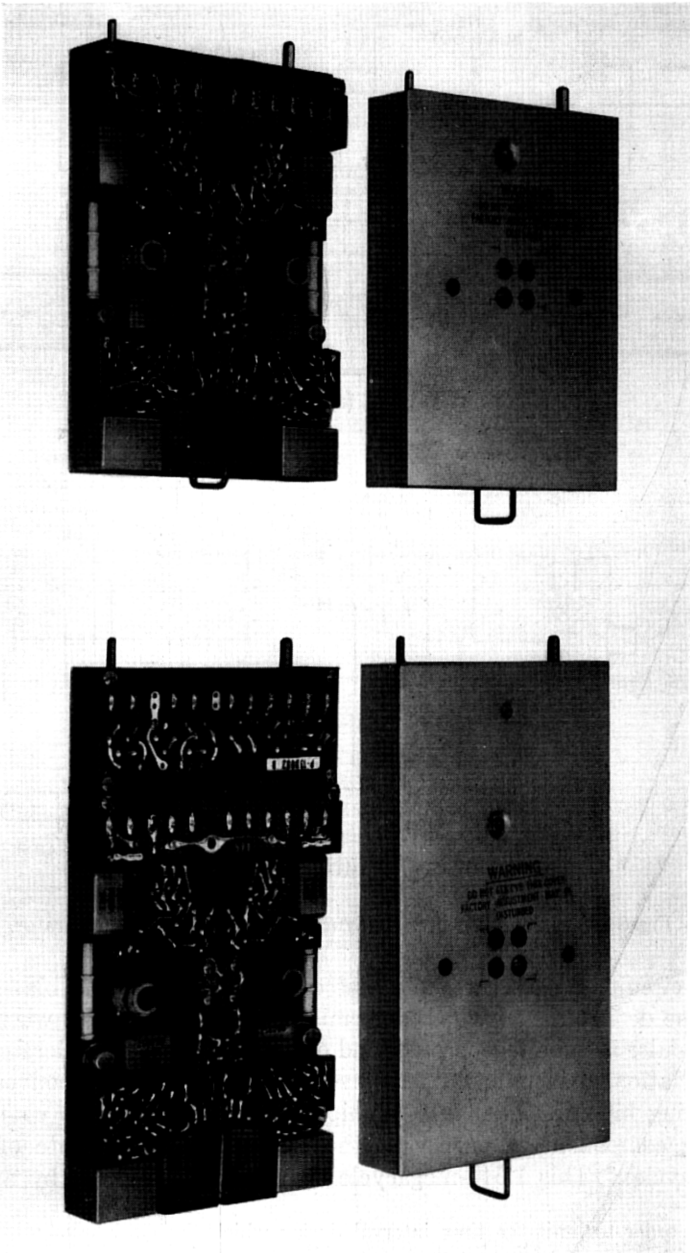

Fig. 9 — 201A and 205A line repeaters.

circuit, amplified, and shaped in the clock circuit to provide a turn-on and turn-off timing pulse for the beginning and end, respectively, of each pulse position. Two gates are provided, one for each polarity of signal pulse, and corresponding blocking oscillator pulse generators. Whenever an incoming signal pulse of either polarity coincides in time with the turn-on timing pulse, the pulse generator of the same polarity is triggered to send out a new pulse. With a normal, error-free signal, the gates and pulse generators operate alternately.

The production units are coded as 201A and 201B repeaters without surge protection and 205A and 205B repeaters with secondary surge protection. Fig. 9 is a photograph of 201A and 205A repeaters with and without covers. The A codes are for use in one-cable installations (both directions of transmission in the same cable sheath) and the B codes are for two-cable installations (the two directions of transmission in separate cable sheaths). The A and B codes are indentical except for the wiring of the connector and the power looping options. With a single cable-splicing pattern for all repeater cases, bi-directional or uni-directional operation in the cable may be chosen by filling all cases in a span with one code or the other.

Repeaters in underground cable systems without aerial exposure do not require lightning surge protection. If there is aerial exposure, however, protection must always be provided. The primary protection is the standard carbon block type which limits the maximum longitudinal or metallic surge to 600 volts peak. In addition, the 205-type repeaters contain secondary protection which consists of a series string of parallel oppositely poled diodes bridged across each incoming pair with 5.6 ohm current-limiting resistors in series with each wire on the line side of the diode string. This arrangement effectively limits the surge to 50 amperes, a tolerable value.

Line repeaters are normally mounted in manholes or on poles in complements of 25 in cylindrical, hermetically sealed apparatus cases. The repeater positions are arranged in five columns of five repeaters each. The 25 connectors, placed in a rectangular pattern at the back of the supporting structure with its 25 guide slots, are wired in the factory to a stub cable which is spliced by normal techniques into the main cable. Any pairs in the apparatus case not used for T1 carrier may be used for voice transmission by plugging into the appropriate positions either through connectors or voice loading coils as required.

Two sizes of case are available. The 466-type, about 10 inches in diameter, is used for 201-type repeaters, and the 468-type, about 2 inches larger in diameter, for the larger 205-type repeaters. The 468-

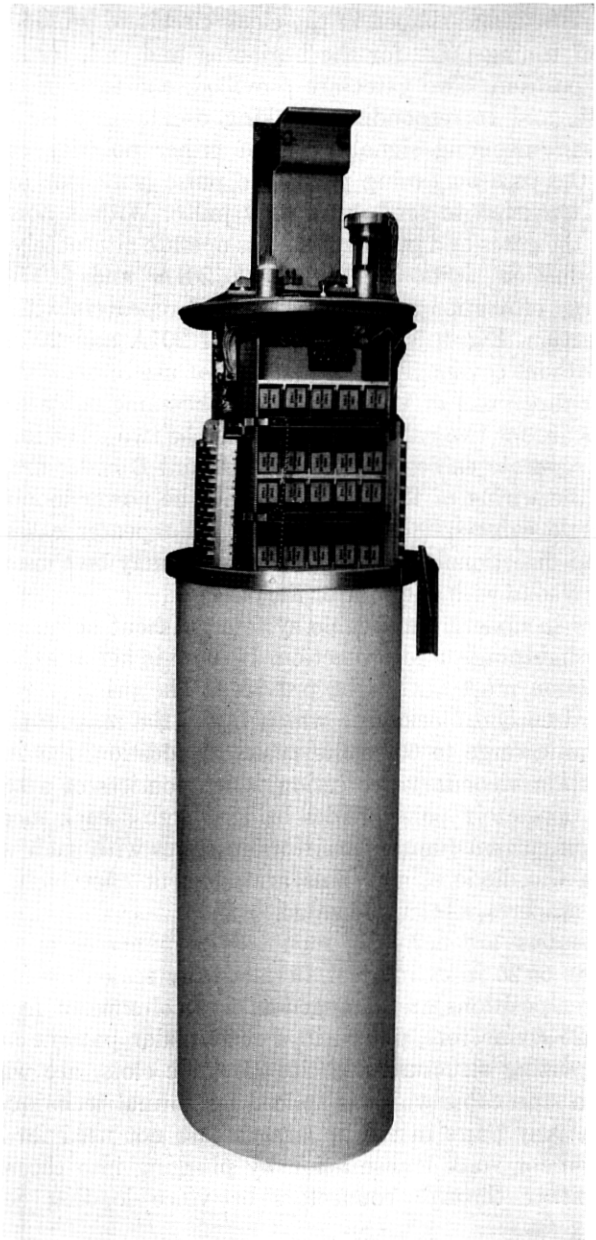

Fig. 10 — 468A apparatus case with cover partly removed.

type case also provides carbon blocks, one on either side of the repeater structure. Both cases provide a fitting for order wire terminals and a shelf for mounting a fault-locating filter which connects to all repeater positions in parallel. Fig. 10 is a photograph of a 468A apparatus case with the cover partly removed to show two rows of repeaters. For cramped locations, either the 466 or 468-type case is available with the cover in two sections fitted together with a gasket and O-ring.

For special service routes not expected to grow beyond four lines plus one spare, a shorter case of each diameter is being standardized to accommodate a single row of 5 repeaters. All other features of the 466A and 468A cases are also provided in the shorter cases.

Power for a string of repeaters is provided from a central office over a simplex loop consisting of the two pairs which feed through each of the repeaters. Looping may be done at any repeater by using the screw options provided, or may be done at a distant central office. Looping at a repeater is illustrated in the system block schematic of Fig. 1. The line current also serves as sealing current for unsoldered splices. Each repeater has a nominal voltage drop of 10.6 volts, and the voltage drop due to the resistance of a normal line section is of the same order of magnitude, depending on its length and wire size. The power is supplied from available office batteries, usually −48 v, +130 v, or −130 v as required. For the longest loops, two batteries of opposite polarity may be used for the two ends of the power loop. Line current is maintained at 140 milliamperes by a current regulator in each office repeater. In older installations the line current is adjusted by a fixed value building-out resistance at the central office so that the nominal line current at the highest expected line temperature is 140 milliamperes. At lower temperatures, the current is larger and may be as high as 200 milliamperes at −40 degrees for aerial cable. The repeaters are designed to operate over a temperature range of −40 degrees to +140 degrees Fahrenheit. This is the range expected to be encountered in pole-mounted repeater cases. Manhole temperatures range from about 25 degrees to 85 degrees F.

3.4 *Office Repeaters*

Two physical arrangements exist for mounting office repeaters: a shop-wired office repeater bay, and an installer wired assemblage of repeater mounting panels. The shop-wired office repeater bay has only recently been placed in manufacture. Most of the present office repeater bays consist of combinations of bank terminating assemblies and span terminating assemblies. Both arrangements provide the functions indicated above for the office repeaters, and both arrangements are capable of the nominal assignment and cross-connect philosophy presented above. The line capacity, jack access points and physical arrangement of regenerators in the shop-wired bay are more convenient than in the older arrangement. However, the two arrangements are fully compatible in the same office.

The outstanding difference between the two arrangements is that the plug-in units for the new bay are specialized office repeaters. These office repeaters each contain a single regenerator, an individual line current regulator, transformers for simplexing the power onto the line, and access jacks. The old span terminating assemblies mount regular 201B line repeaters and a separate control circuit for administering the line powering. The jacks are part of the mounting assembly. Since the 201B repeater contains two regenerators and regenerators are used only on incoming span lines, two incoming span lines are coupled together physically in a common office repeater. In two-cable operation, this coupling is not too objectionable because it also occurs in all line repeaters, but it has greatly complicated the administration of one-cable installations.

Operationally, the other major difference is that both incoming and outgoing jacks for each line are provided in the new bay where only incoming jacks were provided before. With the older arrangement, the only access to an outgoing line is at the circuit to which it is cross-connected. In addition to simplifying spare line patching, the additional jacks allow temporary cross-connections to be made via patch cords and eliminate the need for the access jacks on the bank terminating assembly.

The new repeater bay terminates 75 span lines (three complements of 25) while the older bay only terminates 72. Both bays are arranged for connection of any or all of these span lines to D1 banks or data terminals. Thus they possess a cabling capacity for connecting to 1.544-megabit office equipment of 150 or 144 pairs, respectively (half incoming and half outgoing). When a central cross-connect field is used, this cabling capacity is used to extend the span lines to the central cross-connect field, and D1 banks or data terminals are terminated directly on the cross-connect field.

IV. PERFORMANCE

Prototype models of T1 equipment were field tested between Newark and Passaic, New Jersey. Trunks between various combinations of switching units in the Newark and Passaic buildings were routed over T1 carrier channels. Commercial service was provided over these trunks for about one year beginning July 25, 1961. These field tests, which employed an underground cable, were followed by field tests over an aerial cable in Akron, Ohio, during the last half of 1962. Early production terminals and repeatered lines were used in Ohio.

Measurements made during the New Jersey trial, the Ohio trial, and at a number of the early installations indicate that the following performance is representative of properly functioning T1 carrier systems:

4.1 *Channel Frequency Characteristic*

Fig. 11 shows the frequency response of a typical 2-wire T1 channel. Low-frequency loss has been deliberately added to improve the low-frequency stability of the channel and to control the generation of quantizing noise in the channel resulting from the quantization of input low-frequency noise such as power line hum. A rather gradual roll off at the top edge of the band has been accepted as a compromise in lieu of higher filter costs. For completeness, the transmitter and receiver contributions to the over-all frequency characteristic are also shown in Fig. 11.

Except for input signals above +3 dbm at 0 db system level (SL), the channel frequency characteristic is essentially independent of input signal level.

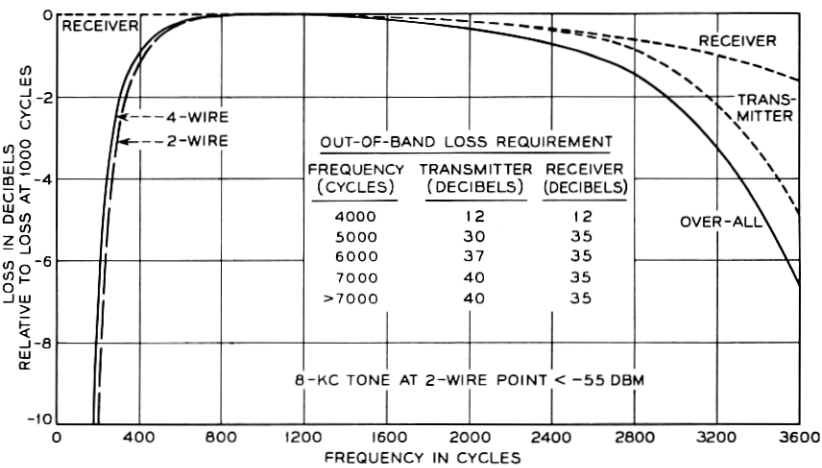

Fig. 11 — Frequency characteristic of a typical T1 carrier channel.

4.2 *Load Characteristic*

The peaks of a +3 dbm sine wave applied at the outgoing switch of a trunk composed of a T1 carrier channel will just cover the full amplitude range of the coder. Larger voltage peaks will be clipped. T1 carrier limits the maximum input signal at a lower level than has generally been common for carrier systems. In frequency division carrier systems the primary problem in achieving load capacity is the generation of intermodulation products in the common amplifiers. If a large number of channels are multiplexed together, the average talkers contribute the primary portion of the load on the common amplifier rather than the occasional high peaks of a few loud talkers. Therefore, a common amplifier designed for the bulk of the talkers will pass occasional high peaks in a individual channel without significant penalty. Provision of the dynamic range in the channel equipment is not expensive. Consequently, rather high overload capabilities have usually been provided. With individual channel coded PCM, the consequences of the choice of full load signals are more specific. Increasing the overload by 6 db costs another digit in the code group, if other performance characteristics are to be maintained; or, looking at the choice in a more practical way, for a fixed compandor characteristic and a fixed number of digits in the code group, a direct exchange may be made between full load signal amplitude and noise in the absence of signal. The subjectively most satisfactory choice is to reduce the noise in the absence of speech to a low level. Therefore, both the full load signal and the noise in the absence of signal are somewhat lower for T1 carrier than for many other carrier systems.

The general shape of the load characteristic is given by Fig. 12. Individual channels will display fine ripples on this basic characteristic caused by the particular match of the input signal to the quantizing grid. Also, if the channel net loss is measured at a frequency very close to a submultiple of the sampling frequency, time variations in the net loss will be observed as the phase relation between the input signal and the sampling time varies.

4.3 *Noise in the Absence of Signal*

Subjective evaluations of telephone transmission are made on the basis of articulation and naturalness of the received speech when speech is being transmitted and on the basis of noise and crosstalk when no speech is being received. It has long been recognized that the noise may be allowed to be higher in the presence of speech than in its

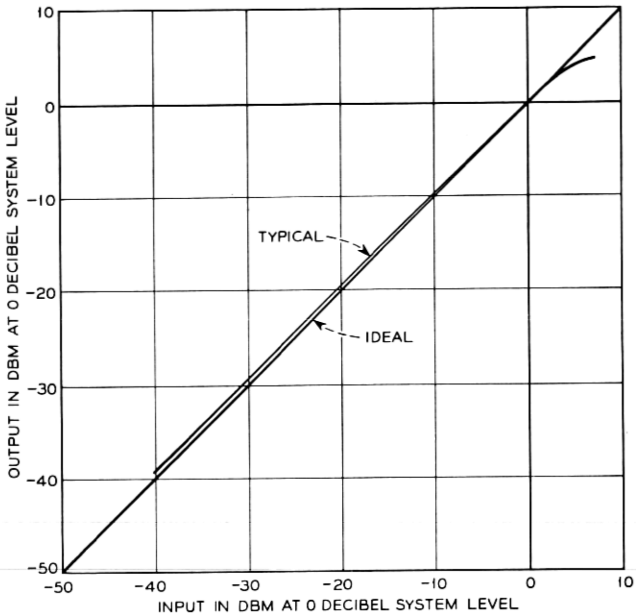

Fig. 12 — Load characteristic of a typical channel.

absence. It also appears that if the articulation and naturalness of the circuit are reasonably good, practically all of the subjective evaluation is made during the absence of speech. Therefore, this characteristic is very important in the subjective evaluation of most modern telephone systems. Because of its importance, it was concluded that the noise in the absence of speech should be comparable to the noise on existing interoffice trunks provided by cable pairs and type E repeaters.

When no direct signal is being applied at the input to a PCM system, the quiescent input voltage to the coder will be within a half quantum step of the decision point between two code levels. Ideally, the quiescent voltage would always be exactly a half step from the decision point, but in practice it may be much closer. If spurious voltages cause the coder to switch back and forth between two codes, the decoder will generate a square wave with a peak-to-peak amplitude equal to the step size.

It was decided that a reasonable size for the quantizing step at the origin was about 70 db smaller than the full coder amplitude range. Since a +3 dbm sine wave encompasses the full dynamic range, a

−67 dbm sine wave will just fill the voltage range from code 63 to code 64 (the first code step from zero). If the coder is switching between 63 and 64, the power in the square wave at the decoder output will be −64 dbm because the power in a square wave is 3 db larger than the power in a sine wave with the same peak-to-peak amplitude. If the transitions between code 63 and 64 occur at random time intervals, the output will approximate random noise. Noise at the system input may trigger these coder transitions when the quiescent input voltage is very close to a decision level. In this situation the output noise will be approximately 24 dbrn at zero level C-message weighting. If the quiescent input voltage is nearly midway between decision levels, input noise may not switch the coder, and the input noise is suppressed. In this situation the major contributor to channel noise is the receiving amplifiers and gates.

If crosstalk from test tones or other sources of periodic signals should happen to control the switching between codes, a periodic wave may appear at the channel output. If the fundamental of this wave is in the middle of the audio band, the weighted noise output may rise to 26 dbrn C-message.

Fig. 13 gives a distribution of the observed output noise at 0 SL, with the opposite end of the channel terminated, as measured by a Western Electric 3A noise measuring set with C-message weighting. Since the amount of noise in a channel depends upon the relative position of the decision level and the quiescent input to the channel, it is a function of individual channel gates and biases. This gives rise to the variation between channels in a system. Since these biases will also change with time, the noise in a particular channel will change with time. Recordings of noise on the Newark-Passaic systems show that the noise power on a particular channel was quite stable with time, indicating that these bias voltages change significantly only over a period of several days.

4.4 *Signal-to-Distortion Ratio*

Fig. 14 shows the signal-to-distortion ratio for a channel as a function of input signal level. This curve is the result of a measurement of the total distortion power introduced by the channel when a sine wave of 1100 cycles is applied at the input. The distortion power is the sum of the quantizing error power for the compression characteristic employed and system imperfections.

Subjective evaluations, using regular telephone sets, of the received

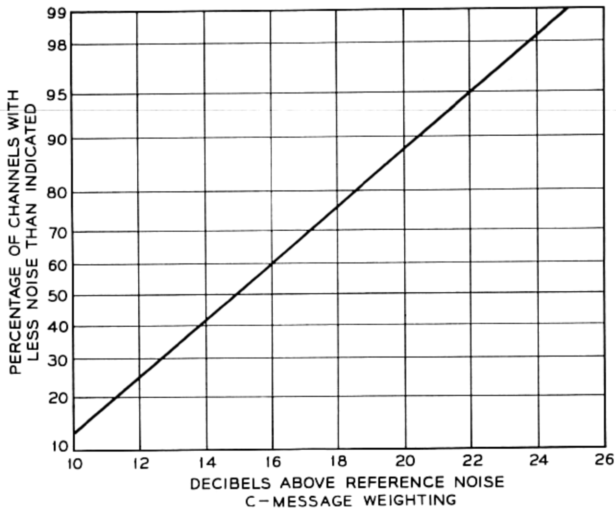

Fig. 13 — Noise in the absence of signal, referred to 0 db system level (far end of channel terminated).

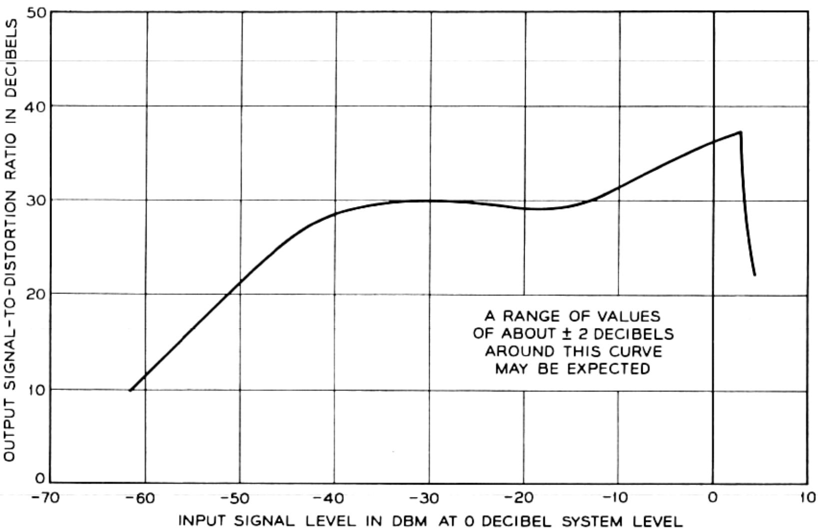

Fig. 14 — Signal-to-distortion ratio for a typical channel.

quality of speech that has been transmitted over a T1 channel have shown that a single T1 link is generally indistinguishable from a physical circuit with 20 dbrn of white noise and the same loss and bandwidth for speech levels between −40 and −10 VU. Clipping distortion is discernible at higher speech levels and critical observers experienced in the sound of quantizing distortion can discern the effects of quantization at lower speech levels. However, the quality is satisfactory over the speech volume range from 0 to −50 VU.

V. SYSTEM ALIGNMENT AND MAINTENANCE

In T1 carrier systems, as in most other multi-channel transmission systems, the techniques required for aligning and maintaining the transmission medium are quite different from those required for terminals. Lines and terminals may even be administered by separate organizations in the operating company.

When a line and its terminals are connected together and put into service as a working system, still another class of problems arises. One problem is the need for immediate indication of a system failure and rapid identification of the defective part so that service may be restored quickly. Another problem, where channels connect to switching systems, is the sudden load imposed on the switching equipment when many channels fail simultaneously and as a result of the failure send false signals interpreted by the switching mechanism as multiple demands for service.

Treatment of these considerations in the T1 carrier system will be discussed in the order mentioned: lines, terminals, system failures, and trunk processing.

5.1 *Repeatered Line Maintenance*

The stub cable which connects the repeater apparatus case to the main cable contains four pairs in addition to the transmission pairs required for the 25 repeater positions. One pair in the stub cable connects the fault-locating filter in the case to the fault-locating pair in the main cable as described in another paragraph in this section. One pair is a spare. The other two pairs are used, at least in the first apparatus case at each repeater location, to carry through a voice order wire which connects, through an access position on the office repeater bay at one end of the span, to office battery and to the switching circuits in the office. A lineman can bridge the order wire terminals on the outside of the case with a portable telephone set and dial any desired number to request assistance. He can also establish a talking circuit with another lineman on the same order wire and drop off the office switching selectors for the duration of his usage of the line.

Each repeater is adjusted in the factory to an optimum slicing level for an incoming signal which has been attenuated by a normal line having 31 db loss at 772 kilocycles. A threshold bias circuit in the repeater described earlier maintains near optimum slicing level over a range of signal variation of ±4 db from this nominal. For optimum repeater performance, each line must be built out to within a few db of the nominal 31 db loss by installing, in the associated repeater, one of a series of 836-type line build-out networks, which are available in sizes from zero to 24 db in 2.4-db steps. To select the proper size, measurement of the transmission loss of each pair from apparatus case to apparatus case is made using a 113A test set at each end. The test set is a small, battery-powered unit containing a crystal-controlled oscillator with preset output amplitude and a calibrated detector marked to indicate directly the code of the repeater build-out network needed for the repeater connected to the pair being measured. Access to the pairs is through a fixture which is inserted into a repeater position and is connected to the set by a flexible cord. The test frequency is 650 kilocycles, near the peak of the normal signal energy distribution characteristic, but differing from it to avoid interference into working systems. A photograph of a 113A test set is shown in Fig. 15.

Before repeaters are installed in a line, they are given a pre-installation test using a repeater test set together with a fault-locating set and an error-detecting set. These three sets are shown in Fig. 16. The combination of sets applies a repetitive pulse train at a nominal input level to the repeater under test, adds a controlled amount of interfering signal, monitors the transmission of pulses, and tests for bipolar violations. The repeater test set also makes a voltage breakdown test of the insulation between repeater circuit and case, and tests for transmission of pulses after insertion of the selected line build-out networks.

When the line has been powered, ready for use, its operating capability is established by two types of test. The first type, which can be made at any time without disturbing the transmitted signal, is a bridging test to determine that pulses are being transmitted and are free of errors. The transmitted signal may be derived either from a working terminal or from a test set. The presence of pulses and of errors, if there are any, is indicated by the error-detecting set. This set, which is powered by the 48-volt office battery, may be bridged across the output of any terminal or office repeater by patching into a moni-

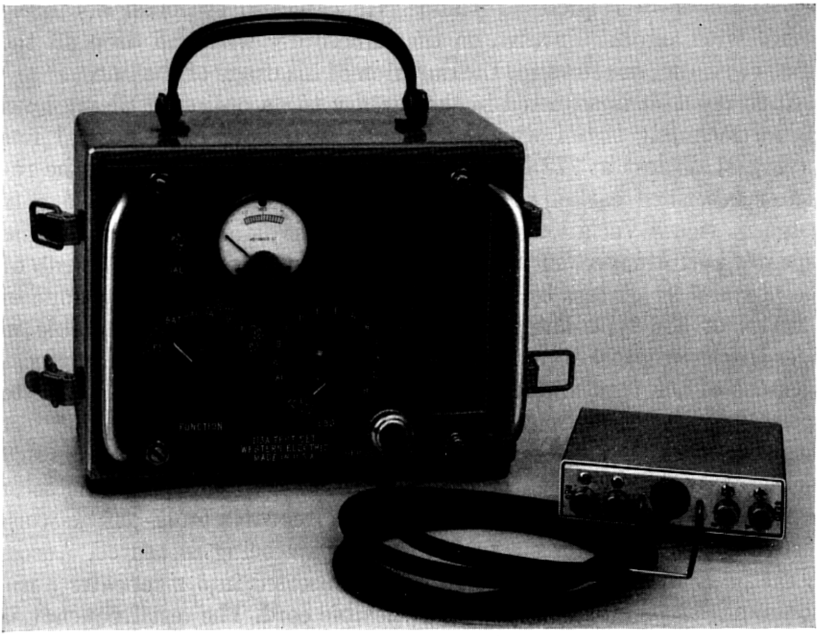

Fig. 15 — 113A test set.

tor jack provided for each span or bank output. A small indicator lamp on the test set panel flashes for each bipolar violation occurring in the transmitted signal. When a panel switch is operated, the lamp lights continuously to indicate the presence of pulses. Since a single error always produces a bipolar violation and since errors rarely occur in pairs or longer sequences, each bipolar violation always represents at least one error, and usually only one.

The second type of test can be made only when the line is not in service. It consists of introducing a test signal containing deliberate bipolar violations of adjustable violation density whose violation polarity is reversed at an adjustable audio frequency rate. This signal is produced by the fault-locating set. The output of each repeater driven by such a signal contains an audio frequency component whose frequency is the reversal rate and whose amplitude is roughly proportional to violation density, within the range of repeater capability. This audio frequency output is used to identify defective repeaters in the span by a test at a span terminating office. The fault-locating filter in each apparatus case along the line is a narrow-band selective

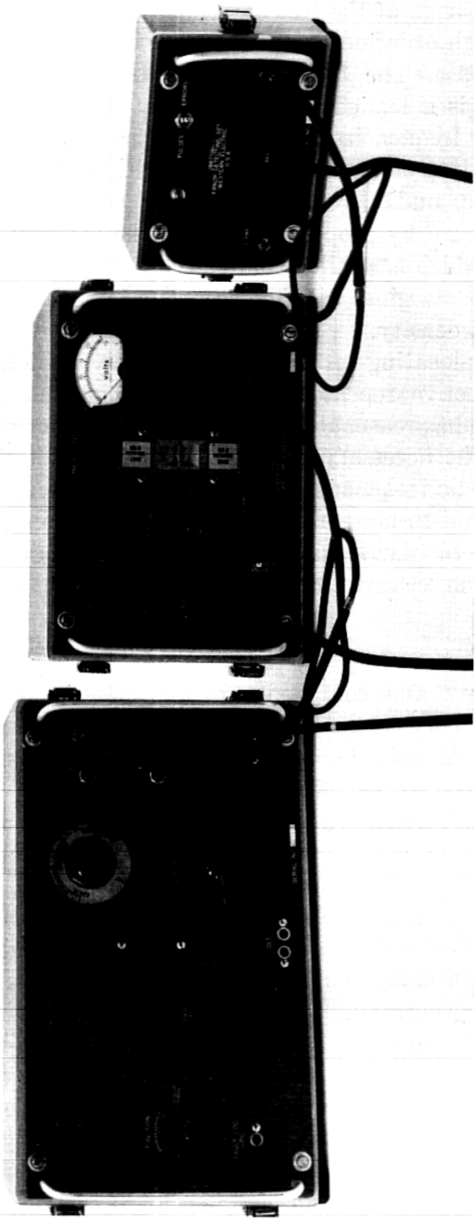

Fig. 16 — Repeater test set, fault-locating set, and error-detecting set.

filter centered at one of a series of 12 audio frequencies within the adjustment range of the test signal generator. The filter input is multipled through isolation networks to the outputs of all repeaters in the apparatus case. The filter output is bridged on the fault-locating pair, which is a loaded voice frequency line, together with filters of other center frequencies at other repeater points, and carried back to the transmitting office to be measured with a noise meter. In a normal working line, audio frequency outputs can be observed from each repeater in turn by properly adjusting the reversal rate of the signal. A repeater which has failed completely will not return an audio signal. One which is marginal will return a signal which is not proportional to the violation density.

This fault-locating test is useful not only in determining the location of defective repeaters but also in confirming that a properly working line has reasonable margins. The fault-locating set is arranged to provide the necessary pulse patterns for the test and to filter the returning audio frequency signal, thereby improving the effective fault-locating signal-to-noise ratio of the fault-locating pair. The set can also provide bipolar signals of adjustable pulse density for use in the preinstallation testing of repeaters in the repeater test set.

5.2 *Terminal*

The variety and complexity of the plug-in units composing the D1 channel bank render its alignment and maintenance a problem of considerable magnitude. Detailed analysis of defects in such circuits requires high-speed oscilloscopes with sophisticated time-scale features and highly trained specialists to operate them. Since application of such methods on a large scale in plant operation seems impractical at the present time, other approaches must be used.

The greatest maintenance simplification, of course, is that the nature of a defect within a plug-in unit need not be identified. A defective plug-in unit is normally replaced by a spare and returned to a repair center where equipment is available to analyze defects in detail.

As another aid to alignment and maintenance, several specialized test units, shown in Fig. 17, have been designed to plug into one of three access points in the circuit, normally filled by through-connectors. These access points, marked by crosses in Fig. 3, are in (*i*) the PAM 3 lead, which carries pulse amplitude modulated signals from the decoder to the expandor, (*ii*) the PAM 4 lead, which connects the expandor output to the receiving gates, and (*iii*) the transmitting and receiving line leads at the alarm control circuit.

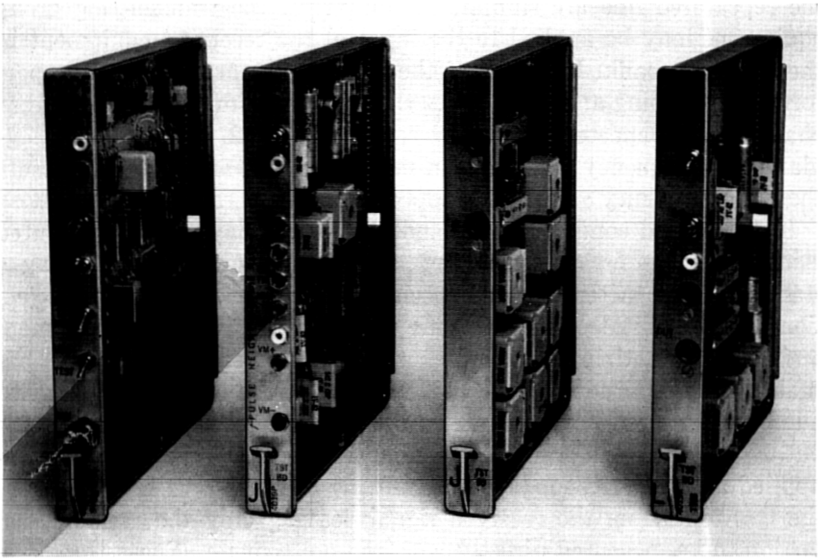

Fig. 17 — Test units used for alignment and maintenance testing of D1 banks.

One of these test units contains a code generator and a code detector. The code generator produces a digital code, timed by the master clock in the transmitting circuit, which represents a 2000-cycle sine wave signal of maximum amplitude in one channel. This signal is impressed on the receiving D1 bank, passed through the receiving converter, decoder, and expandor, and is finally converted into its equivalent voice frequency tone in another special test unit called a PAM detector. The amplitude of this tone is measured by a standard voice frequency transmission measuring set and is adjusted to its proper value by the expandor gain control, the only alignment required in the receiving group equipment.

The code detector portion of the code generator and detector is a device which converts a train of pulses to a direct current ouput, except that it does not respond to the code for zero signal, which is a single pulse at D2 time. Thus, the transmitting D1 bank is adjusted for zero signal by setting the encoder biases for a null reading of the code detector direct current output. The gain of the transmitting D1 bank is adjusted by using the previously adjusted receiving bank as a digital detector to indicate that the proper digital code is being transmitted when a standard voice frequency input is impressed.

Since the normal signals in the two directions of transmission on the repeatered line are similar, the output of the transmitting group equipment may be applied to the input of the receiving equipment in the same D1 bank. Insertion of the code generator and detector performs this looping and also phases the receiving timing circuits so that channel 1 is connected to channel 7, 2 to 8, 6 to 12, 13 to 19, etc. Regular voice frequency transmission measuring sets are used to measure the voice frequency gain of the looped circuit.

In the looped condition, compandor tracking may also be measured using the transmission measuring set, and idle circuit noise using a standard noise meter. A third special test unit, a one-kilocycle rejection filter, facilitates measurement of distortion due to misalignment and to the quantizing noise which results from reconstructing the actual signal amplitude only to the accuracy of the nearest of a limited number of discrete levels. Patched between the receiving channel output and a noise meter while a harmonic-free 1000-cycle test tone is applied at the corresponding transmitting channel, this filter removes the test tone from the received signal, leaving only the residual distortion to be measured directly with the noise meter. These three test units, together with standard transmission testing equipment, are adequate for normal D1 bank alignment and evaluation procedures.

A fourth test unit is provided, however, to aid in identifying a defective plug-in unit. This is the trouble location network, which has three functions. The first is to indicate pulse rate, and the second is to indicate pulse height. The test unit converts these parameters to dc signals measurable by a voltmeter. The third function is to loop the analog output of the compressor to the input of the expandor, eliminating from the loop the encoder, decoder, and converters.

Another necessary maintenance adjunct is a matching network unit for interconnecting the 600-ohm balanced circuits of transmission measuring equipment to the 2500-ohm unbalanced circuits available at the channel unit access jacks. It mounts separate transmitting and receiving circuits which may be used simultaneously for loop measurements. It contains only passive elements such as jacks, matching transformers, resistance pads, and level adjusting keys, and is permanently mounted at a convenient working level at the side of one of each group of four D1 bank bays.

5.3 *System*

An alarm control unit, one of the normal complement of plug-in units in each D1 bank, is specifically designed both to indicate trouble conditions and to aid in identifying the part of the system affected.

The trouble condition indicator is a circuit which continuously monitors the incoming framing signal, the only unique signal always transmitted in a normally working system. The amplified framing signal normally holds an alarm relay operated. If the signal fails, the relay releases and operates audible and visual alarms in the receiving office. At the same time, it forces the transmission of a special signal in the opposite direction. The special signal consists of the normal bit stream with all pulses in digit one and digit eight positions inhibited. The forced absence of these pulses is detected in a second alarm control unit circuit at the far-end D1 bank. This circuit also operates audible and visual office alarms. Thus, if transmission fails in one direction, alarms are operated almost simultaneously at both ends of the system. Different colored lamps on the alarm control unit indicate whether the alarm is due to the primary framing signal failure or the forced failure of digits one and eight.

Sectionalization of the failure is accomplished by manually operating a looping key on the alarm control unit at each end. If both looped terminals indicate normal framing signals, the system failure must have been in the repeatered line. If either looped terminal is out of frame, that terminal must be defective. Since the direction of transmission of the system failure is known from the original alarm indication, it is also known whether the transmitting or receiving portion of a defective terminal is at fault.

If a system failure is due to a defective line, a spare line may be quickly patched in to replace the defective section. Thus, service over the system may be restored at once, thereby reducing the urgency of the time-consuming fault-locating procedures and replacement of defective repeaters.

If the defect is in a terminal, established trouble-location procedures are followed until the defective plug-in unit is identified and replaced. Most such troubles are quickly found by the straightforward application of simple rules. As an aid in identifying the occasional obscure case of trouble, a list of known trouble symptoms is provided, and under each heading a list of the types of units which have been found in manufacturing testing to produce each symptom, arranged in order of frequency of occurrence.

5.4 *Trunk Processing*

Since T1 carrier, like most other carrier systems, sends a continuous signal in the signaling path of each channel when it is idle, a cessation of the signal constitutes a demand for service. If a system fails while many of its 24 channels are idle, the simultaneous cessation of signal in those channels imposes an abnormal load on the switching equipment, which may temporarily impair its responses to normal service demands immediately thereafter. In the case of busy channels, a system failure may affect only one direction of transmission and may not send the proper supervisory signals to stop charges on toll calls, even though the circuits are useless. The system may also continue to accept calls which cannot be completed because of the failure.

To minimize the impact of a system failure on the switching equipment and on customer service, a carrier group alarm circuit, as shown in Fig. 18, is normally provided as an optional accessory. Such a circuit at each end of a system makes or breaks relay contacts as required in each channel during a system failure to produce the least service disruption. Enough contact arrangements are provided, by screw-down options, to process on an individual channel basis any of the types of trunk circuits which may be transmitted over T1 carrier. The carrier group alarm circuit is actuated by the alarm control circuit of the D1 bank with which it is associated, and because of the design of the T1 carrier office alarm system already described, operates almost simultaneously at both ends of the system for a failure in either direction of transmission. Both the system alarm and the carrier group alarm are self restoring so that when a system failure is cleared, the trunks are automatically put back in service. To guard against rapidly recurring service interruptions due to possible intermittent system failures, the carrier group alarm restoral is normally delayed by approximately ten seconds after the system is performing satisfactorily. Since

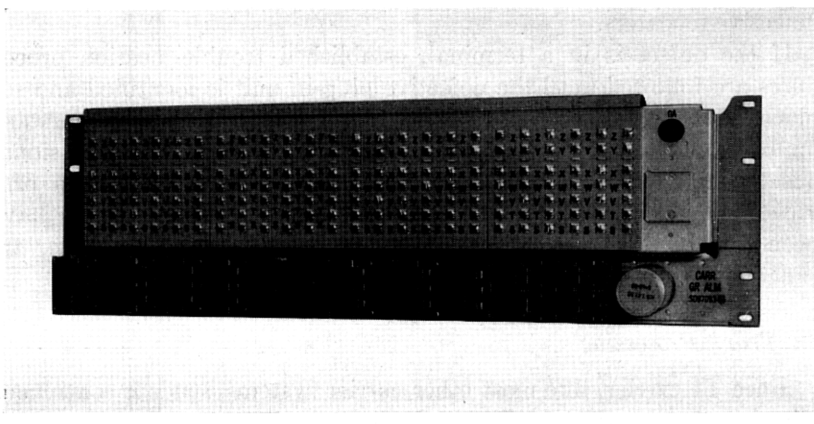

Fig. 18 — Carrier group alarm.

the amount of delay is not precisely controlled, an additional interlock feature, using the signaling path of one of the channels, ensures that the restoral will be simultaneous at both ends of the system.

Twelve carrier group alarm units can be mounted on an 11-foot 6-inch bay, 23 inches wide. The bay is usually placed in the middle of a group of four D1 bank bays, and hand-wired by the installer between the 12 D1 banks and the trunk appearances for these banks on the office distributing frame.

VI. MANUFACTURING TESTING

6.1 *D1 Bank Units*

Of the 15 types of plug-in units which compose the group equipment of a D1 bank, 9 are primarily digital circuits and pose few obscure or unusual problems of inspection testing or adjustment in the factory. Requirements for pulse amplitude, pulse width, and phase are not usually critical, and normal inspection procedures are found adequate to ensure correctness of unit assembly. This is largely true also of the transmitting and receiving gate circuits, which include analog transmission paths as well as digital circuits. They do not require unusually high precision except for the maintaining of high balance in the transmitting gates, which is sometimes a problem in device manufacture. The four remaining units, which do require a high degree of care in assembly and precision in testing, are those involved in analog-to-digital conversion. They are the compressor, encoder, decoder, and expandor circuits.

The compressor and expandor circuits include several amplifiers which must maintain high gain over a wide frequency band with a high degree of stability in spite of aging or variations in temperature and battery voltage. Success in meeting these requirements, however, depends less on advanced manufacturing and testing techniques than on adequate design of feedback circuits and proper choice of stable components. A few routine measurements of gain with and without feedback are sufficient to ensure high performance.

The point where unusual care and precision are required is the measurement and adjustment of the nonlinear network elements. The compressor and expandor nonlinear networks are designed to have identical current-voltage characteristics when measured in the circuits in which they operate. The required inverse characteristics are obtained by their method of connection into the circuits, as illustrated in Fig. 19. For the compressor, a current proportional to the signal is injected

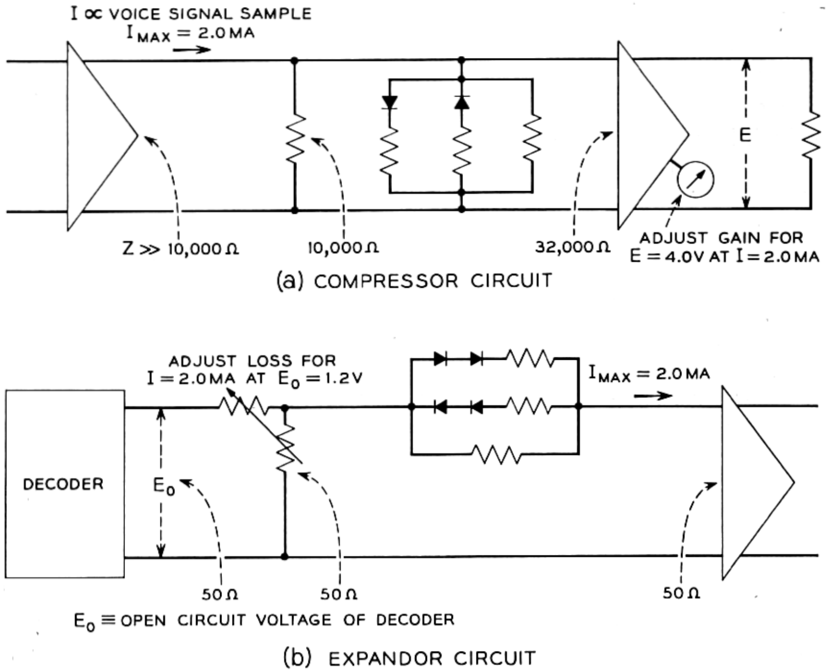

Fig. 19 — Basic operating circuits of nonlinear networks in compressor and expandor.

into the network, and the corresponding voltage is read out and transmitted through the system to the expandor. For the expandor, the voltage is impressed on the network, and the corresponding current is read out as the received signal.

A practical objective for the accuracy of duplication of nonlinear networks is that at any network current within the usable range, the voltage difference between any two networks should not exceed one half code step, one part in 126 of maximum positive or negative signal. This ensures that the maximum error in any signal sample due to mistracking is no greater than the maximum error due to quantizing. Implicit in this statement of the objective is the consideration that absolute magnitudes of nonlinear network voltages are not critical as long as the normalized characteristic shape meets the objective. Normalization is easily accomplished in the circuit by properly adjusting associated circuit gains or losses to match particular nonlinear networks.

In the expandor, a two-element pad, adjustable in small steps, builds out the precisely measured dc voltage at the maximum signal current of 2 milliamperes, to the normal maximum voltage, 1.2 volts, delivered by the decoder. The pad is assembled as part of the expandor network. In the compressor, the gain of an amplifier following the nonlinear network is adjusted until the peak output signal voltage is 4 volts, its normal maximum, for an impressed sine wave input signal of 2 milliamperes peak value.

Assurance of the desired characteristic shape is attained in two steps by precision dc measurements of the voltage of each diode at three values of current corresponding to 0 db, −20 db, and −40 db with respect to maximum signal current of 2 milliamperes.* In the first step, at the device factory, diodes at the normal operating temperature of 120 degrees C are paired within close voltage limits at the middle current for use in the opposite polarity legs of the same network. The absolute voltages also must fall within broad limits, as must the voltage ratios for upper and middle currents and for middle and lower currents. In the second step, at the network assembly factory, the diodes are installed in their operating environment, again a nominal temperature of 120 degrees C. Building-out series and shunt resistors are selected by test and permanently installed so that voltage ratios of the over-all network for the same pairs of test currents are within close limits about the nominal values which produce the desired shape of characteristic.

Table I gives in abbreviated form the translation between input signal and digital code on the line. For a well aligned system, the quiescent input voltage to the coder is about half-way between the decision voltages for codes 63 and 65. A sinusoid as large as about −67 dbm must be applied at 0 db System Level before through transmission will occur. Table I gives the largest sinusoid that may normally be applied to a channel without exciting code levels farther from the origin than the range indicated.

Close control of the diode operating temperature is maintained by careful mechanical arrangement of the diodes, a sensitive, vacuum-sealed, bimetal thermostat, and a heating coil within a reflectorized, vacuum-insulated, cylindrical glass container. An assembled network and its major components are shown in Fig. 20. The mechanical construction of the core is designed to provide thermal low-pass filtering so that the wide temperature excursions of the heating element result in thermostat temperature variations of about 1 degree and diode tem-

* These procedures are discussed in greater detail in Ref. 5, pp. 187–189.

TABLE I

Input Signal Power at 0 db System Level Point	Range of Quantizing Steps Transcended by Peak-to-Peak Excursion of Input Sinusoid
−67.0 dbm	64 min − 64 max
−58.5	63 min − 65 max
−52.9	62 min − 66 max
−46.3	60 min − 68 max
−41.3	57 min − 71 max
−37.0	53 min − 75 max (check point)
−33.5	49 min − 79 max
−30.1	45 min − 83 max
−26.5	41 min − 87 max
−21.7	36 min − 92 max
−17.0	31 min − 97 max (check point)
−12.5	26 min − 102 max
−8.4	21 min − 107 max
−4.6	16 min − 112 max
−1.6	11 min − 117 max
+0.9	6 min − 122 max
+3.0	1 min − 127 max (check point)

perature variations well within the objective of ±0.1 degree C. The design allows for a small overshoot in the thermostat temperature in both directions of temperature change so that just before contact closure or just after contact opening, the relative contact velocity is a maximum. Noble metal contact material is used to prevent contact sticking. Transistor amplifier control of the heating element reduces the contact current and voltage to about 5 milliamperes and 5 volts, respectively.

Many of these nonlinear networks, six per system, have been operating successfully for more than three years, and increasing numbers for shorter periods, with few observed changes in characteristics. The thermostats, cycling at an average rate of about once per minute, give almost no evidence of deterioration.

The encoder and decoder also are high-precision circuits and include logic switching elements which must be unerring in their operation. It is possible to test the separate elements of these circuits by conventional means and to make over-all measurements of the 127 individual code levels using precision equipment. This procedure, however, is laborious and time-consuming. For quantity production, specialized test equipment has been developed which greatly simplifies over-all evaluation and also aids in identifying logic circuit errors where they occur.

The encoder test set consists of a linear generator which provides a uniformly varying encoder input, a word generator which produces in sequence the binary 7-digit codes expected at the encoder output, and a comparator which counts the disagreements between the actual encoder output and the word generator. The ramp generator is adjusted to cover the encoding range from maximum negative to maximum positive signal at the rate of one code step per eight words at the normal encoding rate. The word generator repeats each word eight times before proceeding to the next code. Thus the total number of errors divided by 127, the number of codes, gives the average encoding error in eighths of a code step. An oscilloscope display of the ramp and corresponding code patterns affords an effective means of localizing defective logic elements.

The decoder test set is the inverse of the encoder set. A word generator, of the type used in the encoder set, sends a sequence of digital codes into the decoder. The output, ideally a linear ramp, is displayed on an oscilloscope and is evaluated visually. Here again, the nature of the display aids in identifying logic errors.

6.2 *Over-all Group Test*

When the 29 plug-in units which compose the group equipment of a D1 bank have been manufactured and tested individually, a final test

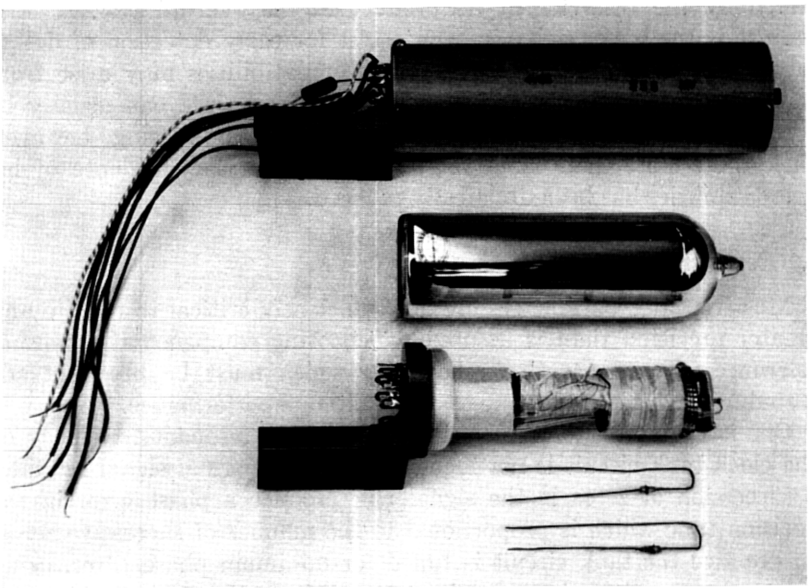

Fig. 20 — Nonlinear network for compressor.

is made of the group assembly. A standard, fully wired D1 bank framework is used as a test position, and tests of the group parallel those which will be made by the operating company in the final installed position.

This type of test has several valuable features. The first, and perhaps most important, is purely statistical. Experience shows that individual plug-in units of this type which have been through normal manufacturing, inspection, and testing routines, have about a 1.6 per cent probability of being defective in a second test. An assembly of 29 such units, therefore, would have almost a 50 per cent probability of a defect. A D1 bank which has successfully met its requirements as an assembly, however, has only a 4 per cent probability of a defect on a second test. A second feature of the over-all test is that it permits individual unit tests to be abridged with impunity. For example, many units have multiple outputs from one transformer. Considerable effort can be saved in testing individual units by measuring only one of these outputs, with the assurance that defects in the other output circuits will be recognized in the over-all test. Similarly, human errors in identifying units for the assembled bank are recognized when the assembly is tested. Experience has also shown that misadjustment of an individual unit test set may sometimes be detected by the behavior of its product in the over-all test. A final feature is the opportunity in such a test for early detection of design incompatibilities among units. Such incompatibilities may arise from any of a wide variety of causes, but once recognized can usually be corrected easily. The value of this feature is diminishing, however, since after more than three years of production the incidence of incompatibilities has been drastically reduced.

6.3 *Repeater Adjustments*

Most repeater parameters are not sufficiently critical to require any greater precision than is assured by choosing components of normal tolerances. There are three, however, which must be precisely adjusted for each regenerator to assure maximum performance.

One is the tuning of the clock circuit. If the resonant frequency of the clock tank circuit is not identical with the normal signal bit rate, a succession of zeros in the signal will produce a phase error in the decision time which is proportional to the number of successive zeros. In practice the tank circuit is tuned for minimum phase jitter, using a test signal adjusted as closely as possible to the nominal bit rate. The pulse pattern of the test signal is alternately sparse and dense, and minimum jitter is marked by the sharpest zero crossing of the superimposed pulse patterns as observed with an oscilloscope at the clock circuit output. Deviations of the clock tuning due to environmental or other influences may be measured by varying the test signal bit rate for comparison with the nominal.

A second critical parameter is the adjustment of the automatic threshold bias circuit. This circuit normally holds the threshold decision amplitude at the center of the eye over a range of about eight db of input pulse amplitude variation. The adjustment is made by sending a normal minimum-amplitude signal of random pulse pattern, adding an interfering signal of such amplitude that one error per second is produced, and varying the bias until the interfering signal, holding the error rate constant, is a maximum. Experience shows that the precise shaping of the input signal pulse is very important. No network of lumped constants has been found which shapes a regenerated pulse properly. For shop testing, therefore, a special cable in a hermetically sealed container is used to simulate the characteristics of the most frequently encountered exchange cables.

The third adjusted parameter is the energy of the regenerated output pulse. The amplitude of the received pulse depends primarily on the energy of the output pulse and the loss of the line. In order to leave as much margin as possible for environmental variations of line loss and for inaccuracies due to the 2.4-db step size for line build-out networks, it is desirable to keep the output energy as uniform as possible. This energy is approximately proportional to the product of pulse height and pulse width. The pulse height is proportional to the power supply voltage, which may vary ± 10 per cent from nominal because of manufacturing variations of the regulator diode which determines it. The pulse width depends to some extent on the switching time of the blocking oscillator transistors, but is adjustable in the clock spike generator circuit. This circuit turns on each pulse to be regenerated with a positive spike and turns it off with a negative spike after an interval determined by the circuit parameters. The interval is adjusted until the amplitude of the output pulse, attenuated by a standard artificial line, has its nominal value. The duration of the positive and negative pulses is matched by pairing transistors at the device factory for matched switching time.

6.4 *Environmental Test*

A major consideration in repeater manufacture is the need for maintaining exceptionally high quality of product. In large population centers, repeaters are mounted in hermetically sealed cases in manholes, often in busy streets of high traffic density. Since it is expensive and time-consuming to open a manhole to replace a repeater, every effort is made to ensure that each unit is in good operating condition when it is put in place and that its failure rate in service is as low as possible.

Each dual repeater contains 145 electrical components and approximately 500 soldered connections. If a quality objective is set to allow no more than one defective repeater in 100, this translates into one defective soldered connection in 50,000 or one defective component in 14,500. Shop experience in the manufacture of similar types of equipment indicates that higher failure rates than these are to be expected with normal manufacturing and inspection methods.

Early in the preparatory stages of manufacture, therefore, it was decided that two extraordinary precautions would be taken to improve as far as possible the probability that a repeater when installed would operate properly. One was the provision already described, for making a pre-installation test of each repeater just before inserting it in a system. The other was the provision for temperature cycling of the adjusted, inspected product followed by a final inspection test. Records are kept of the test results and defect analysis, and continuous quality control is exerted to impound any lots which appear to be substandard. The temperature cycling continues for 20 hours and includes five complete cycles from room temperature down to −40 degrees, up to +150 degrees F, and back to room temperature, holding for at least one hour at each extreme temperature in each cycle. At the high-temperature point of the last cycle, the repeaters are removed from the chamber a few at a time and tested while hot to ensure operation at the design maximum temperature of +140 degrees F. After they have stabilized at room temperature, detailed final tests are made to ensure that changes due to temperature cycling have not been appreciable. About five per cent of the product is cycled in a special chamber equipped to monitor operation while the units are held at the extreme temperatures, in this case −40 and +140 degrees F.

VII. CONCLUSION

Many T1 carrier systems have been in successful operation for more than three years. Many more are being installed and put into service in metropolitan areas all over the United States. In general, acceptance has been good. Although new concepts and sophisticated circuitry are involved, the operating company craftsmen have been able to align and maintain these systems with evident success. Equipment prices were slightly lower from the beginning than the preliminary estimates, and have since been reduced further. The demand for systems has been greater than anticipated so that the manufacturing program has been increased each year over earlier long-range forecasts.

As T1 carrier usage in the plant increases, it is to be expected that needs for connection to other types of trunks will develop. As such markets materialize, the design of additional types of channel units will be undertaken.

Looking to the future, it seems certain that the next few years will see increasing use of the T1 carrier line as a transmission facility for high-speed digital data. Its inherent capability for pulse transmission at the 1.5 megabits per second rate coupled with its relatively low cost make it particularly attractive. This subject is discussed in a companion paper. The expected growth of the T1 carrier trunk network in coming years will greatly facilitate these data transmission applications.

VIII. ACKNOWLEDGMENTS

Contributions to the development of the T1 carrier system have been made by the authors of papers listed as references, their associates, members of Bell Telephone Laboratories development and engineering groups, and members of Western Electric Company and American Telephone and Telegraph Company engineering groups. Particularly valuable have been the earlier work of O. L. Williams, A. C. Longton, and N. E. Lentz, and the continuing efforts of F. H. King, E. J. Anderson, and C. D. Donohoe.

REFERENCES

1. Davis, C. G., An Experimental Pulse Code Modulation System for Short-Haul Trunks, B.S.T.J., *41*, January, 1962, p. 1.
2. Mayo, J. S., A Bipolar Repeater for Pulse Code Signals, B.S.T.J., *41*, January, 1962, p. 25.
3. Aaron, M. R., PCM Transmission in the Exchange Plant, B.S.T.J., *41*, January, 1962, p. 99.
4. Shennum, R. H., and Gray, J. R., Performance Limitations of a Practical PCM Terminal, B.S.T.J., *41*, January, 1962, p. 143.
5. Mann, H., Straube, H. M., and Villars, C. P., A Companded Coder System for an Experimental PCM Terminal, B.S.T.J., *41*, January, 1962, p. 173.
6. Travis, L. F., and Yaeger, R. E., Wideband Data on T1 Carrier, B.S.T.J., to be published.
7. Cravis, H., and Crater, T. V., Engineering of T1 Carrier System Repeatered Lines, B.S.T.J., *42*, March, 1963, p. 431.