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Loop Plant Electronics:

Digital Loop Carrier Systems

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This article examines the reasons for developing large pair-gain digital carrier systems, describes two such systems that were developed for Bell System application—namely, the SLM™ *Subscriber Loop Multiplexer System and the* SLC™*-40 Subscriber Loop Carrier System—and discusses in detail several circuit designs used in the* SLC*-40 System. The* SLM *system is described and its application history is discussed. Also, the experience gained from the* SLM *development and its impact on the development of* SLC*-40 and the Loop Switching System (*LSS*) is reviewed. A detailed description of the* SLC*-40 equipment and system operation is presented next. The introduction of this system into the operating telephone companies is also covered. The final section, which discusses circuit innovations that make the* SLC*-40 system possible, includes details on channel unit dc signaling and the multiplexer.*

I. INTRODUCTION

The loop electronics overview to this issue[1] examines the need for pair gain systems in the loop plant and traces the history of these systems. This article examines briefly the reasons for developing large pair-gain digital carrier systems developed for the Bell System, the *SLM*™ Subscriber Loop Multiplexer System and the *SLC*™-40 Subscriber Loop Carrier System; it then finally discusses, in detail, design breakthroughs which made the *SLC*-40 system possible.

In the late 1960s, P. A. Gresh of Bell Laboratories and C. D. Howe of AT&T[2] studied the long subscriber route characteristics of the Bell System and concluded that the optimal size for a single carrier system would be between 75 and 100 lines. This size system could serve the largest amount of long route growth and save the most capital compared to a cable design. This analysis influenced the design of the *SLM* system, the first Bell Laboratories design of a large pair-gain digital system.

A digital approach was chosen in 1967 when the *SLM* system design began, since a digital system offered the potential for high transmission quality and low cost with newly available integrated circuits. Further, digital systems offered the potential of lower cost by using time division concentration at the remote terminal, and could use the T1 trunk carrier hardware for the digital line.

The *SLM* system, first introduced in the Bell System in 1971, is a combination carrier and concentrator system that has an 80-line capacity. The *SLM* system uses delta modulation encoding. The line concentration designed into the *SLM* system provided for 80 subscriber lines switched to 24 digital channels. Adding full access of all subscriber lines to the carrier channels assured that the probability of blocking would not exceed 0.5 percent more than four times per year.

The T1 trunk digital carrier line was chosen as the basis for the transmission medium for the *SLM* system because of its proven design and good operational experience. Dependable, low cost repeaters and apparatus were already available, eliminating development time and expense. Maintenance methods and test equipment for T1 carrier were already available and proven. Finally, the use of the latest integrated circuit and thin film technologies in the *SLM* system permitted addition of desirable service features into the circuit designs while retaining the potential for low cost.

SLM designers were strongly influenced by the expectation that a multiple remote terminal system, with each terminal having a capacity of 40 lines, could be more useful to the operating companies. In this configuration, simple per-channel adaptive delta modulation codecs (see Ref. 4) offered lower costs than shared PCM codecs duplicated in each remote terminal.

In 1974 the *SLC*-40 system was introduced into the Bell System (Fig. 1). The *SLC*-40 system was a result of the experience gained from the *SLM* system and from breakthroughs in delta modulation encoding which permitted 40 channels to be transmitted over a single T-carrier line, compared to 24 channels for the *SLM* system. The *SLC*-40 system design resulted in a simplified, unconcentrated, high pair gain, low cost system.

After descriptions of both systems are presented in the next two sections, considerably more detail is devoted to those innovations in the *SLC*-40 system which have made it a low cost, high performance system which has made major penetration into the rural plant in the Bell System.

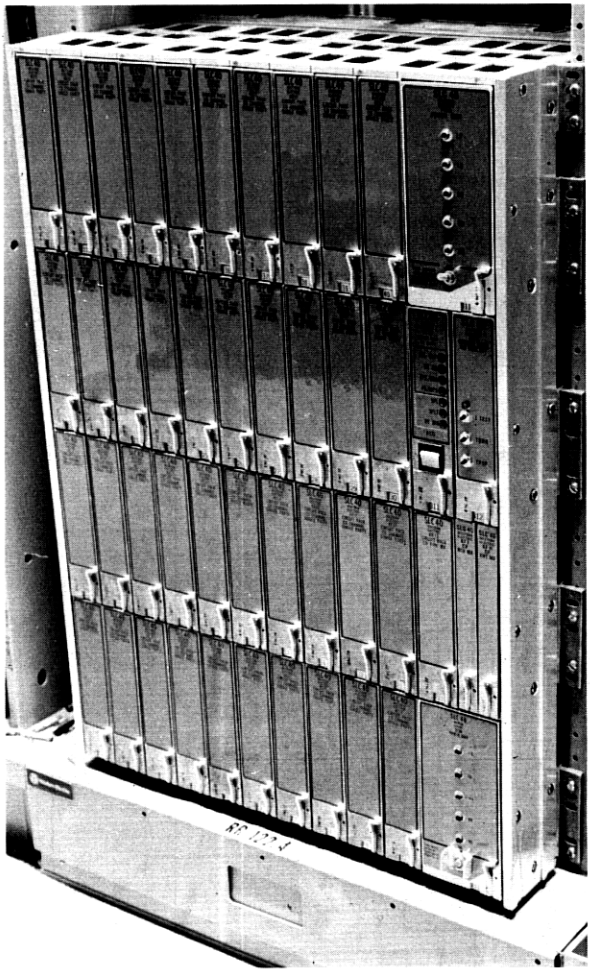

Fig. 1—The *SLC*™-40 central office terminal.

II. SUBSCRIBER LOOP MULTIPLEXER

2.1 Description

The *SLM* system is a digital carrier system that combines switching and carrier to serve 80 customer lines over a T1-type digital line. The system is capable of providing single-party, two-party ANI, multiparty, and coin service. A block diagram of the *SLM* system is shown on Fig. 2.

SLM circuitry was designed to be installed on a "per-line" basis as much as possible. The use of per-line equipment at the remote terminal assures that simple, rapid repairability is possible and also minimizes operating company investment when fewer than eighty customers are served. The customers can be grouped at several locations and still have access to all 24 channels.

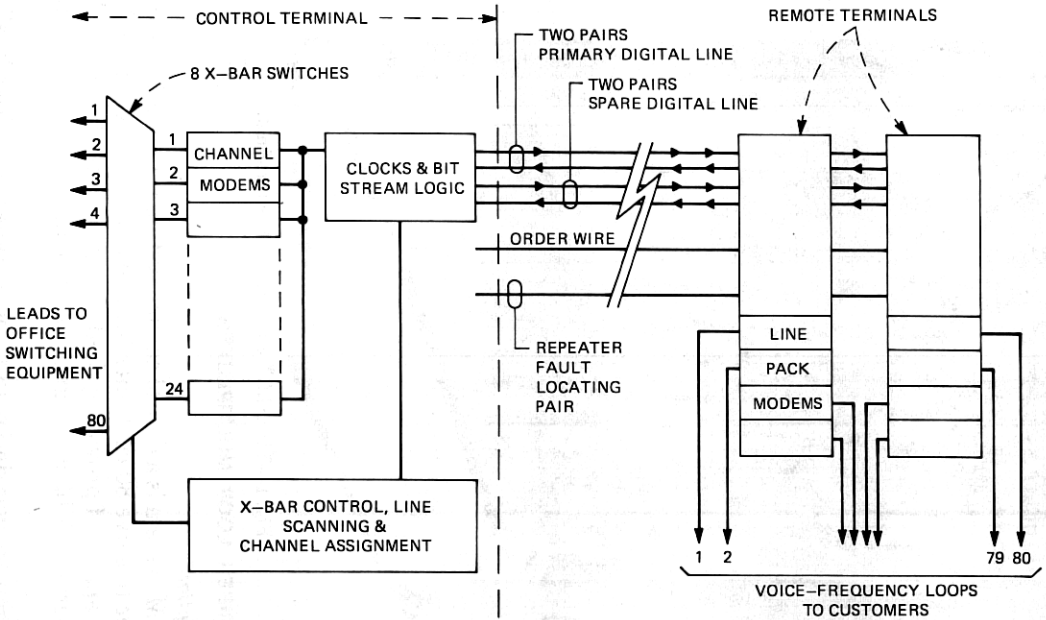

Fig. 2—Block diagram of subscriber loop multiplexer.

To achieve a high pair gain and a low cost per line served, the *SLM* system concentrated 80 lines onto 24 channels. All lines at all remote terminals were provided full access to all channels to assure a low probability of blocking.

The central office expansion from 24 channels to 80 lines is performed by an 80 by 24 miniature crossbar switch. The remote terminal concentration is performed by assignment of one of the 80 lines to one of the 24 channels transmitted over the digital line. The line pack at the remote terminal performs many important functions for each customer's line. It connects the line to the assigned channel, converts analog voice signals to digital signals and vice versa, and performs all line signaling functions such as off-hook detection, dial pulse or *TOUCH-TONE*® transmission, ringing detection and ring trip detection. By including most circuit functions in the line pack, the remote terminal common equipment can be reduced. The line packs can be added only when needed, thereby reducing initial system costs.

The *SLM* system was designed with ease of maintenance as an important feature. By inserting both line signaling and transmission onto the line pack, a per-line trouble can be quickly located, and if the trouble is within the *SLM* system, the line pack can be easily replaced. A per-line testing capability is built into the system that can be accessed from a test desk. This allows diagnosis of the reported trouble prior to dispatching a repairperson.

Extensive alarms of common system troubles were also provided. Automatic equipment checks all channels daily, removes bad channels from service and signals the trouble condition. Common system problems, including channel failure, can usually be repaired by plug-in card replacement.

Several features make the digital line portion of the system reliable. The digital line is monitored for errors, and if the error rate exceeds a threshold, a spare line is automatically switched into service. Also, a remote terminal or a defective portion of the digital line can be disconnected by looping back the digital line at the most distant remote terminal that could sustain service. This keeps the customers in the unaffected portion of the system in service. Additional details on loop electronics maintenance are described elsewhere in this issue.[3]

To attain maximum versatility, the *SLM* system can be operated with up to six remote terminals, as long as the total number of subscriber lines does not exceed eighty. This versatility can be an excellent hedge against uncertain growth.

The designers of the *SLM* system made extensive use of the most recent developments of integrated circuits and thin film substrates to serve many functions at low cost. Their use was essential to provide the logic for delta modulation at low cost and very low power levels. Low power consumption is very important for the remote terminal standby battery design, allowing use of very low maintenance nickel-cadmium batteries.

Additional details on the characteristics and use of the *SLM* system appear in Refs. 4, 5, and 7.

2.2 Experience

A field experiment of the early *SLM* design was conducted in Lawrenceville, Georgia in 1968. The designs were then modified and improved, and the first operational field trial of *SLM* hardware was conducted by South Central Bell Telephone Company in Brandon, Mississippi from October 1971 to October 1972. The first telephone customers were served by this system in December 1971. The Brandon trial verified that the hardware design was satisfactory and that the concentration feature maintained good service with no known cases of blocked calls.

A second trial by Northwestern Bell Telephone Company was held in Duluth, Minnesota to evaluate performance in a cold climate. This trial was a full operational trial; it checked all procedures and documentation in addition to checking the improved hardware designs. Northwestern Bell employees installed and maintained the systems throughout the trial. This system was made operational in December 1972 and the first customers were loaded on the system in February 1973.

The use of the *SLM* system for pair gain applications grew in the operating telephone companies until 1975 when the *SLC*-40 system became available. Since the simplified *SLC*-40 system could serve in similar pair-gain applications and had a significant cost advantage over the *SLM* system, manufacture of the *SLM* system was discontinued in 1977.

Though no more *SLM* systems will be manufactured, the operating *SLM* systems are providing high quality service with low maintenance. The *SLM* system was a pioneer in digital pair gain systems in the Bell System. It has given the operating telephone companies confidence in the ability of current pair gain systems such as *SLC*-40 and LSS[6] to provide reliable, high quality service and to save construction capital investments. It also showed that a system could be designed using concentration that would not limit service due to the traffic.

The experiences and observations gained in the development and use of *SLM* have been useful in selecting features and concepts for more recently developed pair gain systems for subscriber use such as the Loop Switching System (LSS) and the *SLC*-40 system, which will be described in detail later. Some of the more important lessons learned were:

(*i*) T-type digital lines will perform satisfactorily in the loop plant and can be properly installed and maintained by available craftspeople.

Operation of these lines and their low-cost T1 hardware have proven very practical in the subscriber cable environment. The design of these digital lines, supported by computerized techniques, can be readily handled by operating company engineers. T-carrier technology was chosen for the digital line of *SLC*-40. Similar satisfactory performance has been observed on the *SLC*-40 systems.

(*ii*) A well-designed concentrator, with a very low probability of blocking, will perform well in the subscriber loop plant and give excellent customer service. An intracalling feature at the remote terminal is not necessary to provide good service. Traffic studies of *SLM* systems in service showed that the assumptions used for *SLM* traffic design were conservative even in a suburban environment where telephone activity should be higher than in rural communities. These observations supported the conservative traffic design approach that was subsequently designed into the Loop Switching System (LSS).

(*iii*) Several maintenance concepts were reinforced by *SLM* experiences. The need for a spare digital line was confirmed by maintenance tracking studies.[3] Plug-in maintenance was found to be easily performed. Per-line equipment aided in quickly finding single customer problems. Common alarms associated with a small number of common circuit packs helped to simplify system troubleshooting. These features were directly implemented into the *SLC*-40 design.

(*iv*) The feature of allowing up to six remote terminals per *SLM* system did not turn out to be economically viable. The extra cost involved in establishing each remote terminal more than offset the advantages of extra flexibility. Almost all *SLM* systems were equipped with just two remote terminals; only a few had three remote terminals. No more than three were ever used.

(*v*) Finally, *SLC*-40 was the result of continuing work to improve upon the encoding algorithms used in *SLM*. In the course of this work it was discovered that suitable speech quality could be obtained with less than 40 kilobits per second sampling. This made possible a simple carrier system with much lower "getting started" cost than *SLM*, a desirable attribute for application on low-density small-cross-section routes. As it turned out, the IC technology then available made the new *SLC*-40 system lower cost than the *SLM* system at all sizes and led to the phase-out of the *SLM* system.

III. THE *SLC*-40 SYSTEM

The *SLC*-40 system is a digital subscriber carrier system that uses delta modulation to derive 40 full-time voice frequency channels from a single digital line, operating at 1.544 megabits/second over two cable pairs. This section will provide a functional description of the *SLC*-40 system and will describe introduction of the system to the operating telephone companies.

The *SLC*-40 system (shown in Fig. 3) can best be described through its three main components: The Central Office Terminal (COT), the Remote Terminal (RT), and the Digital Line.

3.1 The COT

The COT equipment of an *SLC*-40 system is composed of a central office (CO) channel bank assembly, a jack panel, and a fuse and alarm panel, and is designed to be bay-mounted into an existing or newly placed central office. One 11-foot 6-inch CO frame can accommodate the necessary equipment for up to four central office terminals.

The COT equipment (shown in Fig. 1) provides an interface between the digital signals transmitted over the digital line and the subscriber originated voice frequency signals that appear at CO line equipment terminals and are connected to the main distributing frame. Each channel bank is connected to a main and a spare digital line at the jack panel. The jacks provide access for performance testing of both the channel bank and the digital lines. The channel banks are powered by normal −48 Vdc and optional 130 Vdc office battery via fuses in the fuse and alarm panel, which also contains relays that, when operated, output system alarms to the office. Power sharing resistors that are utilized by the optional current regulator units to power the digital line are also located within the fuse and alarm panel. One jack panel and one fuse and alarm panel provide connecting facilities for four CO channel bank assemblies.

A CO channel bank assembly must be equipped with two types of plug-in apparatus. These are the common circuit packs and the per-line circuit packs, called COT channel units. All seven of the common circuit packs are necessary for proper system operation, while the 40 channel units may be added one at a time to satisfy the demand caused by continued growth in customer service.

The common circuit packs plug into connectors that are mounted within the two right most columns of the four shelf channel bank assembly. The common units include a low voltage power unit that converts office battery into a +5 volt and −8 volt supply for TTL logic and the analog circuits of the channel units, and a line-feed power unit that converts office battery into a current-regulated voltage supply for the digital line. A line interface unit couples either the main or the spare digital line to the line-feed power unit and the digital multiplexer circuit packs, while generating the transmit and the receive clock signals used at the COT. The choice of either main or spare digital line operation is determined within the maintenance unit by monitoring line errors and other system status indicators. The three remaining common circuit packs contain the multiplexer/demultiplexer circuits. The multiplexer/demultiplexer provides parallel-to-serial conversion of the

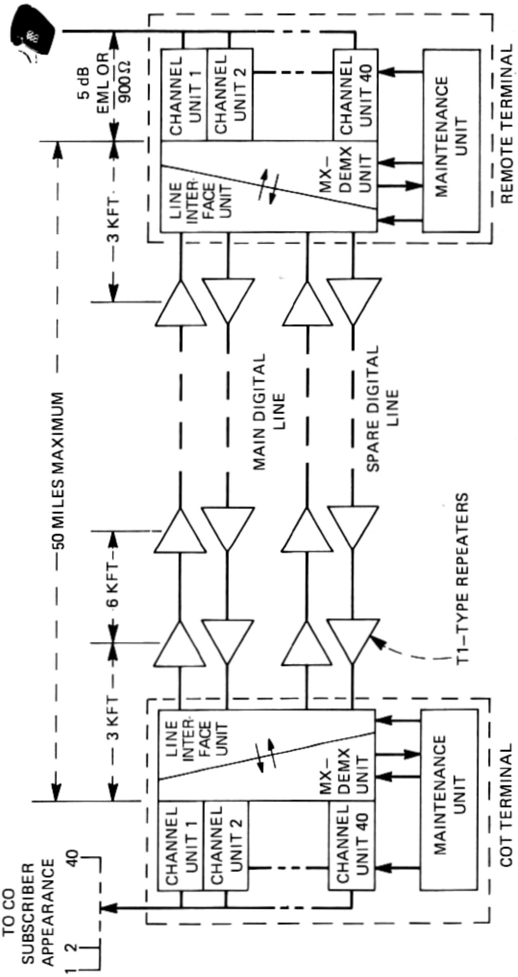

Fig. 3—Typical *SLC*™-40 system.

channel pack output data signals into a transmit data stream and also provides serial-to-parallel conversion of the receive data stream into 40 individual channel pack input data signals. The multiplexer also controls the synchronization of data transmission between the COT and the RT. This function is called framing.

The channel units perform three basic functions: ringing, transmission, and signaling. Each COT channel unit can detect the presence of a ringing voltage applied by the office at the CO subscriber line appearance. When this occurs, the COT channel unit outputs a special digital code that is transmitted to the corresponding RT channel unit. The RT channel unit detects this code and, if the subscriber's station set is not off-hook, applies ringing. The kinds of ringing voltage that can be applied to the subscriber are determined by the type of COT and RT channel units installed. There are three codes of COT channel units, selected according to service requirements; i.e., single-party service, two-party service with ANI, and multiparty service with full selective ringing.

The transmission of voice frequency signals by the COT channel unit is facilitated by the hybrid circuit. The hybrid circuit separates transmit and receive signals, thereby allowing them to be processed individually. The channel unit transmitter low-pass filters the CO signal from the hybrid and encodes it using delta modulation into digital data.[8] The encoder sampling is timed by transmit clock signals from the multiplexer. These signals also cause the data to be output to the multiplexer on the transmit data bus. Independent of the channel unit transmitter, the receive data bus transfers data from the demultiplexer to the channel unit receiver. This data is input to the channel unit at the proper time by a receive clock signal. The data is then decoded by a delta demodulator, filtered, and amplified to standard audio levels. The hybrid circuit directs the resultant voice frequency signal towards the CO.

The COT channel unit also decodes signaling information from the received data. When a subscriber's station set is on-hook, the RT channel unit transmits all ones data to the COT channel unit. There, a dial pulse receiver checks the incoming data for the presence of continuous ones and, if present, forces the dial pulse repeat relay to release. This causes a dc open circuit towards the CO. If the subscriber's station set goes off-hook, a delta modulation pattern (random ones and zeros) rather than continuous ones is transmitted to the COT channel unit. This break in the all-ones data sequence is detected by the dial pulse receiver which causes the dial pulse repeat relay to operate. Thus, dc loop current is drawn from the CO, indicating that the subscriber's station set is off-hook. Dial pulsing, which can be viewed as a series of on-hook and off-hook conditions, is treated in the same manner as loop supervision.

3.2 The RT

The remote terminal of the *SLC*-40 system is configured for both cabinet and frame mounting. The RT cabinet is designed to handle applications where moderate subscriber service growth would normally require feeder cable reinforcement. The RT frame is used when several remote terminals are required at one location or an RT is to be installed inside a building.

The RT cabinet apparatus consists of a three-section weatherproof aluminum cabinet (see Fig. 4) that contains a four-shelf RT channel bank assembly, primary lightning protection, jack access to a main and a spare digital line, a battery compartment that is equipped with a heater, a ringing supply, and an ac powered battery charger. This cabinet can be either pole or pedestal mounted for use with aerial and buried plant.

The RT channel bank assembly is designed to accept 40 RT channel units and seven common units, in a configuration similar to the COT channel bank assembly. The RT common units perform the same functions as those used at the COT, with the major operational difference being that the transmit and receive clocks are both derived from the incoming digital line signal. Located beneath the RT channel bank assembly, another shelf mounts the ringing supply and the battery charger plug-in units. The battery charger uses 117 Vac to develope a nominal

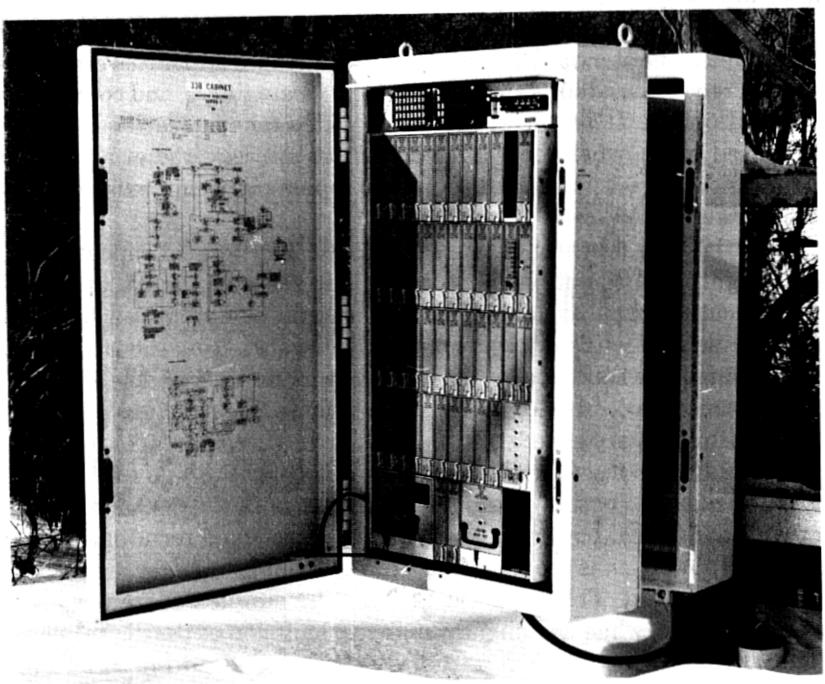

Fig. 4—The *SLC*™-40 remote terminal cabinet.

−43 Vdc that is used to charge the flooded nickel-cadmium battery string, power the plug-in apparatus, and supply talk current. This choice of battery voltage allows dc supervision on subscriber loops to 900 ohms. When ac power is lost, the reserve power stored in the battery string will sustain system operation for at least 10 hours.

The RT frame equipment consists of a 7-foot frame that is factory wired with two RT channel bank assemblies, a common ringing supply, and a fuse, filter, and jack panel. The RT frame must be housed in a PBX-type building environment that includes a signal grade −48 Vdc power supply equipped with stand-by batteries, a cross-connect facility, and primary lightning protection for the voice frequency and carrier pairs. The fuse, filter, and jack panel contains fusing and a filter used to connect the external power supply to the channel bank assemblies and the ring supply. This panel also provides jack access to the digital line, an order wire, and an optional fault-locate pair.

3.3 The digital line

The digital line of the *SLC*-40 system is configured such that apparatus from the T1 carrier system can be utilized. Two-way repeaters are used to regenerate a digital bipolar signal at the T1 line rate of 1.544 megabits/second. The repeaters, typically spaced at 6-kilofoot intervals, are simplex powered over the cable pairs of the digital line.

Two types of repeater apparatus are available for construction of the digital line. The standard T1 configuration includes apparatus cases plus plug-in repeaters, adapters, coil cases, fault-locate filters, and connectors. In addition, the 217-type repeater is provided for applications in aerial or buried plant, where only a few repeaters are required at a repeater point and where it is desired to mount repeaters within existing non-pressurized enclosures.

The 217-type repeater consists of a single 209-type T1 repeater, primary lightning protection via four dual-gap gas tubes, and a connectorized weatherproof housing. This repeater may be removed from the digital line for testing or replacement by disconnecting the stub cable. Provisions for a fault-locate filter are not made in this case since the maintenance procedure for this repeater utilizes the quick-access feature to perform a binary search of the digital line with a portable test set.

Depending on the overall length and gauge of the digital line, the line is powered either entirely from the COT, from both the COT and the RT, or with additional powering from remote power-feed terminals. When multiple power spans are required, a power looping repeater is necessary at each junction. This repeater isolates the simplex current of each powering span, while enabling through transmission of the digital signal. The *SLC*-40 system can operate over either a standard 140 mA T1 line or the new 60 mA low power T1 line, when equipped with the proper power and line interface units. A spare digital line is required with a cabinet-mounted RT.

When an RT frame is used, the two remote terminals in the frame can each have a main and a spare digital line, share a spare digital line, or be connected to a T1 Outstate system, which provides either a 1 for 5 or 1 for 11 protection line switch for the *SLC*-40 systems.

The 1 for 2 spare line sharing option without T1 Outstate is implemented by two relays, one located at the COT jack panel and the other in the RT fuse, filter, and jack panel. These relays are wired so that the spare digital line is connected to system 2 through the normally closed contacts. If system 1, the priority system, needs the spare line, it operates the relays, thereby connecting it to the spare line through the normally open contacts.

To use digital lines provided by the T1 Outstate equipment, special line interface units are required for the *SLC*-40 system. The COT and the RT frame must be wired with the "no spare" option and need not be equipped with line-feed power units, as the digital line is powered through office repeaters located within the span terminating module of the T1 Outstate system. Also, special sensing and switching plug-in units are required at the span terminating module. These units pass bipolar violations that occur on the digital line, thus permitting normal operation of the *SLC*-40 multiplexing and maintenance apparatus (see Section 4.2.2).

3.4 Operating company introduction

A field trial model *SLC*-40 system was first used at Ligonier in the Western Area of Bell of Pennsylvania. The first customers were placed on the system in March 1974. This trial was not just a hardware trial, but rather a full operational trial in which Bell of Pennsylvania staff constructed, installed and maintained the system, using preliminary documentation in the standard Bell System format. All aspects of the trial were successful. Minor hardware and documentation modifications were made for the twelve introduction systems that were produced in late 1974 and early 1975.

The original single party capability has been expanded to include multiparty (four-party) and two-party ANI service. The channel packs for both of these offerings underwent field trial in C&P of West Virginia, multiparty in the summer of 1975 and two-party ANI in the spring of 1976. Both of these trials were successful and these channel packs are now available for telephone company use.

Operating telephone companies requested manufacture of *SLC*-40 remote terminal equipment in a frame for use inside a building. This equipment has use where a building already exists or where a building can be built for a wire center deferral. Also, in cases where a large number f remote terminals are collocated, it may be feasible for cost or appearance to use a small building. Obvious savings are available by eliminating costly cabinets and sharing batteries and battery charging equipment.

The frame-mounted *SLC*-40 system developed to satisfy this need was first used in Winterset, Iowa in a small central office building that had once held a small switching machine. Equipment cutover was completed in the fall of 1976 with no difficulties. This location was also used in early 1977 to field trial extended range channel packs, capable of service out to 1600 ohms beyond the RT. The frame-mounted remote terminal has had good acceptance by the operating telephone companies.

IV. CIRCUIT DESIGNS THAT ARE UNIQUE TO THE *SLC*-40 SYSTEM

4.1 DC signaling: simulating a metallic pair

SLC-40 channel units must transmit dc signaling* as well as voice frequency signals. Since the delta modulator cannot transmit these dc signals, special detectors on each channel unit must recognize when the signals are present, and then command the channel unit at the distant terminal to simulate the signal. The carrier loop thus performs like the metallic loop it replaced, so neither the central office equipment nor the subscriber's station set need be modified for operation with the *SLC*-40 system.

Single-party telephone service requires two kinds of dc signaling: off hook and ringing. When a subscriber served by the *SLC*-40 system goes off hook, an off-hook detector in the RT channel unit senses this condition and commands its corresponding COT channel unit to operate a relay. When operated, this relay draws dc current from the central office, just as the station set would do if it were on a metallic pair. Dial pulsing is treated like a series of on hook and off hook transitions. To ring a single-party phone, the central office applies a 20-Hz voltage on the ring conductor. The COT channel unit, therefore, has a ringing detector which commands the RT channel unit to switch ringing voltage onto the subscriber's ring conductor.

To provide *SLC*-40 service to single-party subscribers at lowest cost, RT and COT channel units are available that are capable of transmitting only the signaling required for single-party service. More complex signaling circuits are required to provide service on multiparty (ONI) lines or on two-party (ANI) lines, and RT and COT channel units with these capabilities are available at added cost.

The following sections describe in detail some of the signaling circuits used in *SLC*-40 channel units.

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* The term "dc signaling" includes 20-Hz ringing, because the 20-Hz frequency is so low compared to VF signals.

4.1.1 Single-party RT off-hook detector

The current design of single-party RT channel unit uses the circuit illustrated in Fig. 5 to power the subscriber's station set, apply ringing, and detect off-hook.[9] The circuit works on loops up to 1600Ω, with up to five ringers,* and it follows dial pulses accurately even under adverse conditions. The circuit has two modes of operation, determined by whether relay K1 is operated or released, and each mode will be described separately.

With relay K1 released, the 48V battery powers the loop through current limiting resistors R1 and R2, and the comparators are used as a two-stage off-hook detector. Resistors R3–R7 form a bridge network, with resistor values chosen such that the output of the bridge $(V_1 - V_2)$ is negative when the "metallic current" $(I_R - I_T)/2$ exceeds 14 mA. The bridge resistor values are also chosen to reject "longitudinal currents" $(I_T + I_R)/2$, caused by 60-Hz induction from nearby power lines, that might otherwise interfere with the off-hook detection.

To avoid wrong numbers, the off-hook detector must not distort the duration of the dial pulses it detects. The circuit utilizes the inductance of hybrid coil "B" for this purpose. After dial pulse transitions (opens or closures) the metallic current does not achieve its steady state value instantly. Instead, its rate of change is slowed by the inductance and capacitance of the subscriber's ringer. If the off-hook detector sensed only the level of current, it would distort the duration of dial pulses under limiting conditions. To prevent this, the bridge is made sensitive to both

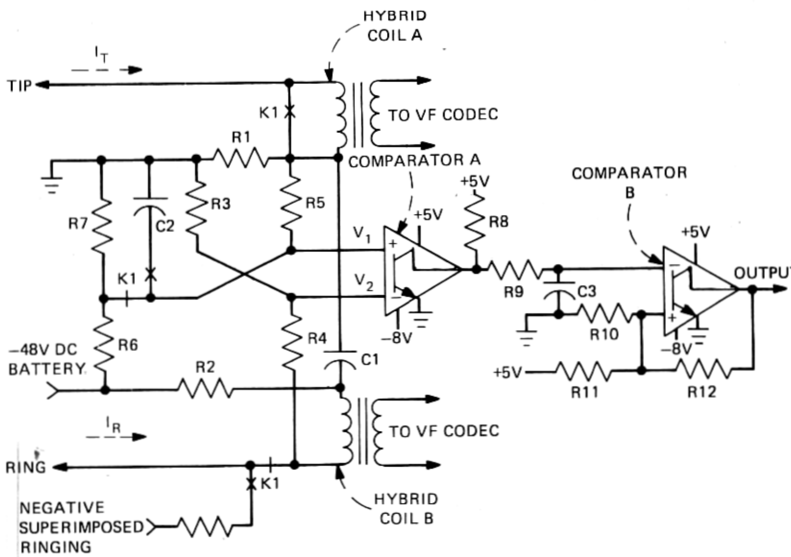

Fig. 5—Single-party off-hook detector.

* For loop greater than 900Ω, the maximum number of bridged ringers is 4.

the level and rate of change of metallic current. The changes in current that occur during dial pulsing develop a voltage transient across the inductance of hybrid coils "A" and "B," and the transient on coil "B" is coupled (via R4) to comparator A. Hence, comparator A's output detects dial pulse transitions with little delay.

The second stage of the off-hook detector (comparator B and associated components) transmits legitimate output transits from comparator A, but it blocks false transitions that can occur under certain conditions. One example of such false transitions occurs if the subscriber has several ringers. The metallic current then may briefly oscillate following the break transition of dial pulsing. This could cause comparator A to detect "split pulses" (more than one make and break transition per dial pulse). False transitions could also occur if one side of the subscriber's carbon block protector faults to ground on a loop with 60-Hz longitudinal voltage (induced from a nearby power line). The faulted protector can then cause a significant 60-Hz metallic current to flow in the loop, which would switch comparator A on and off at a 60-Hz rate. False transitions such as these should not be transmitted to the central office channel unit, where they would be repeated to the central office.

The negative input of comparator B connects to capacitor C3, which charges to +5 Vdc when comparator A detects an absence of metallic current and it discharges to 0 Vdc when metallic current flows. Comparator B changes state when the voltage on C3 crosses the threshold voltage established at its positive input by R10, R11, and R12. Resistor R12 provides hysteresis on the threshold voltage, and the thresholds are chosen such that the filter circuit delays both make and break transitions by 14 msec. Since the make and break transitions are equally delayed, the filter circuit does not significantly distort the duration of dial pulses. If comparator A detects a brief split pulse, the filter circuit prevents this false transition from appearing at the output of comparator B (although this distorts the dial pulse by an acceptably small amount). The hysteresis prevents the output of comparator B from changing states faster than a 48-Hz rate, so 60-Hz switch hook closures cannot possibly be transmitted to the central office.

The second mode of the single-party signaling circuit occurs when ringing is applied to the subscriber by operating relay K1. In addition to switching a negative superimposed 20-Hz ringing voltage onto the "ring" conductor, the relay reconfigures the input to comparator A to detect off hook during ringing (ring trip). In this mode, the ringing current is returned via the tip conductor and R1 to ground. R5 and C2 low-pass filter the ac ringing return voltage, such that V1 does not cross the negative threshold voltage established at V2, while the subscriber is on hook. Consequently, comparator A's output remains high. When the subscriber goes off hook, a dc component flows in the ringing return current, causing V1 to cross the threshold voltage, forcing the output of comparator A low. After 14 msec, the output of comparator B switches high. This releases relay K1 (removing ringing from the loop) and enables the dial pulse detector to detect off hook.

4.1.2 Multiparty ringing detector

This section describes the ringing detector used in the current design of the COT channel unit for multiparty service.[10] The requirement that the COT channel unit detect when the central office applies ringing was previously discussed for single-party service. For multiparty service, the ringing detector must also distinguish which of four different kinds of ringing the central office is applying: 20-Hz voltage superimposed on either positive or negative dc, and applied to either the tip or ring conductor. The multiparty COT channel unit uses the circuit shown in Fig. 6 to detect the presence and polarity of ringing on the ring conductor. An identical detector is used for the tip conductor. These circuits detect ac-dc ringing of 65 to 110 vrms, 17 to 23 Hz, superimposed on ±30 to ±60 Vdc. The net distortion of the duration of the ringing burst is less than 100 msec, and it will not falsely detect ringing as a result of dial pulsing or from up to 40 Vrms of induced 60-Hz voltage on tip and ring. The impedance of this circuit exceeds 5MΩ when measured by a central office's automatic line insulation test, so the central office does not falsely interpret the *SLC*-40 loop as leaky and in need of maintenance.

The 20-Hz detector can be subdivided (as shown in Fig. 6) into a high pass filter, an amplitude to duty cycle converter, and a duty cycle detector. The high pass filter blocks dc while passing 20 Hz. The amplitude to duty cycle converter consists of Q1, Q2, and Q3, and associated passive components. Transistor Q2 turns on during positive ringing peaks, and Q3 turns on during negative peaks. Since the Q2 and Q3 collectors are tied together, capacitor C2 charges and discharges at a 40-Hz rate when ringing is present. The duty cycle when Q2 or Q3 conducts increases as the 20-Hz amplitude increases.

The duty cycle detector prevents transients on the ring conductor from being falsely interpreted as ringing. When actual ringing is present, the duty cycle when Q2 or Q3 conducts is large enough to discharge C2 below the threshold voltage on the positive input to comparator B. The comparator output then switches high, indicating that the central office has applied ringing. Resistor R10 provides hysteresis to avoid multiple output transitions when ringing is applied.

The polarity detector uses zener diodes CR3 and CR4 to isolate C3 from the voltage on the ring conductor when ringing is not applied. When ringing is applied, C3 charges positive through the diodes if the ringing is positive superimposed, or negative if ringing is negative superimposed. Comparator B senses the polarity on C3 to determine the polarity of

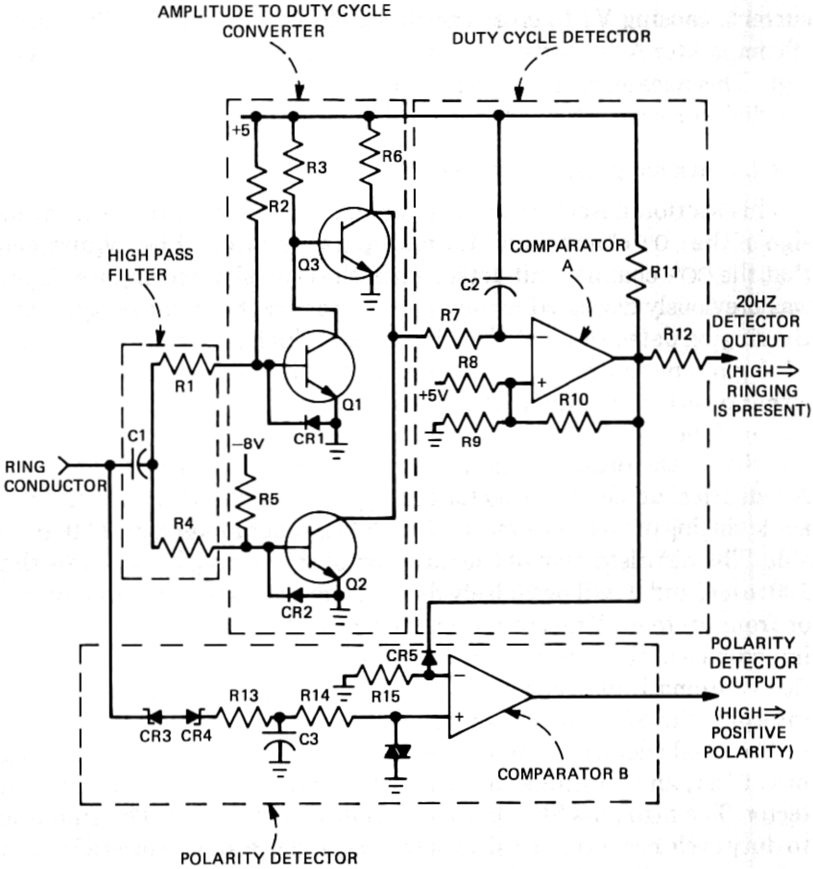

Fig. 6—Multiparty ringing detector.

ringing. The polarity detector operates faster than the 20-Hz detector when ringing is applied, and it releases slower when ringing is removed. This choice of timing prevents the momentary connection of ringing to the wrong party when ringing is applied or removed. Additional circuitry (not shown) prevents momentarily ringing the wrong party during revertive calls.

4.1.3 Applying multiparty ringing at the RT

The state of a COT channel unit's ringing detector must control the application of ringing at its corresponding RT channel unit, and the *SLC*-40 system used a simple but effective technique to do this.[11] For multiparty service, the ringing detector has five possible states, and each of these states causes a unique four bit serial "ringing code" to be transmitted continuously to the RT channel unit (while the subscriber is on hook). The five states and their ringing codes are listed in Table

I. Since ringing is applied only while the subscriber is on hook and the delta modulator is used only while off hook, the ringing codes and the coder can share the 37.7-kb/s data path that links the RT channel unit to its COT channel unit.

The multiparty RT channel unit selectively operates three relays in response to the ringing code, to apply the appropriate ringing condition to the subscriber. These relays are shown in Fig. 7, and Table I indicates the conditions when they are operated. Relay K1 (when operated) applies ringing on the ring conductor. Relay K2 applies ringing on the tip conductor, and relay K3 selects positive or negative superimposed ringing. When no ringing is to be applied, all three relays are released.

The five ringing codes are selected to be easily decoded into operate commands to the three relays. The reader can verify that the decoding circuit (Fig. 8) continuously provides the appropriate operate commands as the ringing code shifts through the shift register. This selection of ringing codes also prevents a defective logic gate in common equipment from unintentionally applying ringing on all channels simultaneously, since the decoder inhibits all relays if it receives continuous ones or zeros. The channel unit disables the relays when it senses off-hook. The shift register, decoding circuit, and other circuitry are contained within a custom integrated circuit.

Table I — Multiparty ringing states and ringing codes

COT ringing detector state	Ringing code	RT relays to be operated
No ringing detected	1111	None
Negative polarity detected on ring	1010	K1
Negative polarity detected on tip	1110	K2
Positive polarity detected on ring	0001	K1, K3
Positive polarity detected on tip	1100	K2, K3

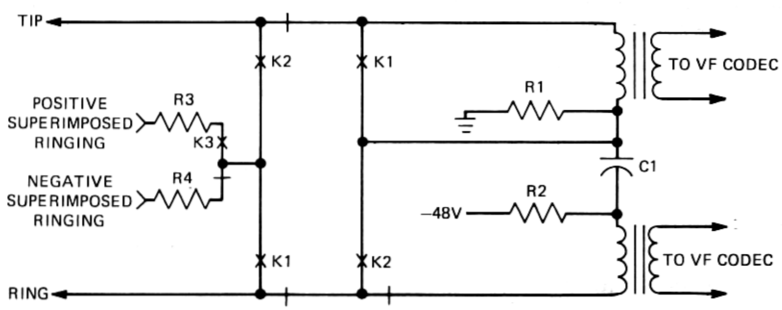

Fig. 7—Ringing relays for multiparty RT channel unit.

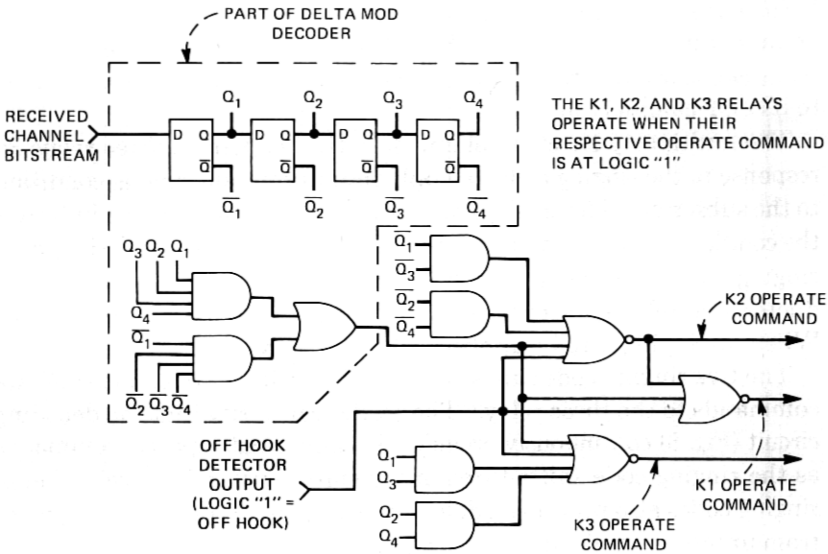

Fig. 8—Multiparty ringing code decoder at the RT.

4.1.4 Channel units for two-party ANI service

RT and COT channel units are also available to serve subscribers on two-party lines equipped for Automatic Number Identification (ANI). The tip party station set on such a line has an identifying resistance to ground (typically 2.65 kΩ) while off hook that allows the central office to determine whether the tip or ring party has initiated a call. Central offices test ANI loops for the identifying ground either between dialed digits or before and after dial pulsing, to assure the reliability of the charging scheme.

The two-party ANI channel unit at the RT tests for tip party ground under command from the COT channel unit.[12] The first test occurs automatically when the subscriber initially goes off hook. The COT channel unit does not repeat this off hook to the central office until the first test is complete. The COT channel unit commands subsequent tests whenever the central office performs a tip party ground test. The circuit that senses when the CO makes a tip party ground test is illustrated in Fig. 9. Relay contact K1 closes to simulate off hook to the central office. When a central office tests for tip party ground, loop current is interrupted, and the COT channel unit senses this condition as an interruption in loop current flow through the optical coupler's LED.

The COT channel unit commands the RT channel unit to test for tip party ground by transmitting a burst of continuous logic 0 for 250 msec. When the RT channel detects this burst, it shorts tip and ring to −48V and checks for longitudinal dc current. If the longitudinal current is sufficient to indicate a tip party ground, the RT channel unit returns a

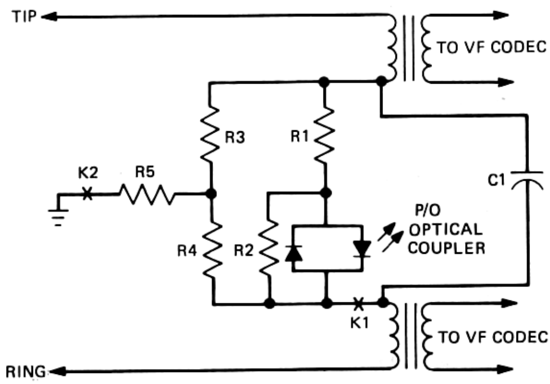

Fig. 9—Channel unit interface to central office for ANI service.

burst of logic 0 to the COT. If dc longitudinal current does not flow (i.e., ring party is off-hook) the RT transmits the delta modulator output instead of logic 0. The COT channel unit examines its received bitstream and operates relay K2 if it receives a burst of logic 0 at the end of the test. The K2 relay contact simulates a tip party ground to the central office, and this indication is maintained for the duration of the call, unless a subsequent test indicates a switch in parties.

4.2 SLC-40 multiplexer: a digital design that is tailored for loop plant operation

The *SLC*-40 multiplexer/demultiplexer provides parallel-to-serial and serial-to-parallel data conversion of the transmit and receive data, respectively, for the channel units and the maintenance unit. The framing circuits of the COT and the RT multiplexer, independent of data generated by the channel units, synchronize these data conversions by monitoring the receive serial data, the frame bit, and bipolar violations. If a loss of synchronization is detected, each multiplexer inhibits data transmission and initiates a "handshake" routine that reestablishes synchronization. The multiplexer also maintains a minimum density of ones in the serial bit stream that is output to the digital line. This function is called zero suppression.

The multiplexer/demultiplexer functions are implemented with the TTL logic circuitry. These circuits are packaged in three common plug-in circuit packs at the COT and at the RT. The transmit and the receive circuit packs used at each terminal are identical. A functional circuit pack is used to specialize the multiplexer for use at the COT or the RT.

The channel unit to multiplexer data interface is provided by a system of ten transmit and ten receive data buses. Each bus connects a column of channel units to the multiplexer. The data on each bus is gated in (receive) or out (transmit) of a channel unit by the channel clocks. These clock signals are generated by the multiplexer with a separate clock phase connected to each row of channel units.

4.2.1 The frame structure

Each frame produced by the *SLC*-40 multiplexer contains 164 sequential bits of serial data that is output to the digital line at the T1 rate of 1.544 megabits/second. The frame is composed of four groups of 40 channel unit data bits and four "housekeeping" bits, as shown in Fig. 10. Every channel unit produces one data bit for transmission in each group, thus the channel units are clocked at 37.66-kHz. The M1 and M2 housekeeping bits transfer system status information between the maintenance units at a 18.83 kilobit/second rate. The remaining two housekeeping bits are produced by each multiplexer and are used to insure that the COT and the RT multiplexer/demultiplexers are synchronized, i.e., in frame.

The frame data sequence is generated by the parallel-to-serial data converter from the channel unit transmit data on the ten data transmit buses. This data conversion is controlled by the transmit frame counter at the COT. At the RT, since the transmit clock is slaved to the receive clock, the receive frame counter can also perform as the transmit frame counter. Thus, at the RT, there exists a fixed relationship between the receive and the transmit frames, unlike the COT, which can accommodate any phase relationship resulting from delay attributed to the length of the digital line. Each receive frame counter controls a serial-to-parallel data converter that demultiplexes the serial bit stream onto the ten receive data buses that supply receive data to the channel units.

The transmit and the receive frame counters are each configured from a four-bit binary counter, a four-bit shift register and two flip-flops. The binary counter, which is clocked at the T1 rate, traverses a 41-state mini-cycle consisting of three 10-state micro-cycles and one 11-state micro-cycle. The state of the shift register controls the length of each micro-cycle and is advanced once per micro-cycle. The two flip-flops are

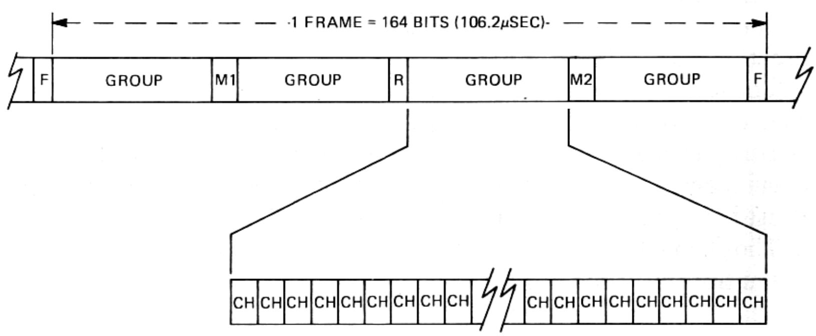

Fig. 10—The *SLC*™-40 frame.

connected as a modulo-4 counter that changes once per mini-cycle of the binary counter and selects the housekeeping bit that is to be inserted into the frame during that mini-cycle. Together these four mini-cycles form a 164-state macro-cycle defining the full period of the framing counter and the length of a frame.

Each state of the frame counter shift register produces a channel unit clock signal. These four clock phases control the transmission of data between the multiplexer and the channel units over the transmit and receive data buses. Each channel unit transmitter utilizes two nonadjacent phases of the transmit channel clock. The first clock phase times the channel unit digital encoder sampling and the second phase enables the output of this data onto a transmit data bus. Two transmit and two receive clock phases are distributed across each row of ten channel units. The primary and secondary role of each clock phase is reversed at every other channel unit.

During the frame counter shift register mini-cycle, the binary counter is clocked 41 times. By advancing the shift register state at half-clock intervals on alternate shifts, symmetrical channel clock phases are produced, which are 10, 10½, 10, and 10½ T1 clock intervals in length. This symmetry makes possible the above-mentioned clock pairing.

The position of each channel unit's data within a group of the frame differs by five time slots between the COT-produced frame and the RT-produced frame. This five time slot offset in channel unit data position within a frame allows a unique test of the COT to be conducted when the COT digital line is looped at the jack panel. This test allows an analog test signal to verify the correct operation of the clocks and data buses at the channel units.

4.2.2 Misframe detection

The multiplexer generates the frame (F) and the random (R) housekeeping bits and inserts them into the transmit data frames (see Fig. 10). The value of the F-bit is determined by taking a modulo-2 sum over the preceding 164 transmitted bits. The resultant parity data is transmitted by F at the end of the frame. The value of F is randomized by the R-bit that is output by a pseudorandom data generator at a rate of one bit per frame. The R-bit is always included in any sum over 164 bits, thereby preventing bits other than the F-bit from consistently exhibiting the value of F.[13]

The loss of synchronized data transmission, a misframe, is determined in the receive demultiplexer by taking a modulo-2 sum over the preceding 164 received data bits and the received frame bit. This sum should be zero; if not, a parity violation has occurred. The detection of two parity violations in any three successive frames forces the receive demultiplexer to initiate the reframing process.

Receive data errors that are caused by noise or crosstalk on the digital line are detected by the multiplexer as bipolar violations. When a bipolar violation is detected during the preceding frame or at the frame bit, the resultant frame parity violation is not accumulated. Thus the misframe detection time increases as the digital line error rate increases.

4.2.3 Reframing

When either the COT or the RT detect that the system is out of frame, they initiate a reframing process. This "handshake" process is accomplished by the cooperative transmission of special synchronization sequences between the COT and the RT. The terminals alternate in their progression through this series of reframing states, where each state is signaled by the transmission of a special data sequence. These special data sequences contain all ones except at the R-bit and the F-bit time slots, which may have a value of zero or one. This results in a fast reframe, because very few frames of parity testing are necessary to verify the frame bit location in the received data stream.

Each multiplexer has two status conditions, out of frame (OOF) and out of sync (OOS), that must be satisfied to complete each step of the reframing process. During normal system operation, both the COT and the RT multiplexers are not out of frame ($\overline{\text{OOF}}$) and out of sync. A multiplexer is not out of sync ($\overline{\text{OOS}}$) during the reframe process when it locates the frame bit in the received special code, and the received data does not satisfy the parity test. Table II shows the transmitted code sequences and identifies each multiplexer's status during individual steps of the reframe process that occurs after the RT multiplexer has detected an out of frame condition. This reframe process lasts for only eight or ten frames if the digital line is error free during the reframe time interval.

Table II — Reframe sequence when misframe is detected at RT

COT multiplexer status	Transmitted data sequence* R	F	RT multiplexer status	Transmitted data sequence R	F	Number of frames†
$\overline{\text{OOF}}$•OOS	Normal		$\overline{\text{OOF}}$•OOS	Normal		—
$\overline{\text{OOF}}$•OOS	Normal		OOF•OOS	1	1	2
OOF•OOS	Alternate 1's and 0's	0	OOF•OOS	1	1	1 or 3
OOF•OOS	Alternate 1's and 0's	0	OOF•$\overline{\text{OOS}}$	1	0	1
OOF•$\overline{\text{OOS}}$	0	0	OOF•$\overline{\text{OOS}}$	1	0	2
OOF•$\overline{\text{OOS}}$	0	0	$\overline{\text{OOF}}$•OOS	Normal		2
$\overline{\text{OOF}}$•OOS	Normal		$\overline{\text{OOF}}$•OOS	Normal		—

* Special reframe sequences are all ones except at the F and R housekeeping bits as shown.

† This count assumes that no bipolar violations occur during the reframe time.

4.2.4 Zero suppression

A zero suppression circuit acts on the serial data stream by forcing a one whenever the minimum ones density is not sufficient to guarantee proper signal regeneration by the digital line. This is seldom necessary with the *SLC*-40 system, however, since each channel unit outputs all ones while not in use by a subscriber, thereby producing a data bit stream with a high density of ones.

The zero suppression circuit utilized in the *SLC*-40 multiplexer forces ones into the output serial data stream such that there are at least N-1 ones in any $8N$-1 successive data bits.[14] Thus the minimum long term (N large) density of ones is 1/8, and it is possible to divide the output data bit stream into eight bit or less blocks, each of which contains at least a single one. Thus a one is forced only when 15 or more adjacent time slots of the frame contain zeros, which requires the 15 channel units associated with these time slots to be active. Under these conditions, a one is forced with a probability of 2^{-15} (approximately 3×10^{-5}), since the probability of a one in any active time slot is assumed to be 0.5 for an active channel. This introduces a negligible impairment to the channel unit decoded signal.

A four-bit binary counter, a flip-flop, and some connecting logic are used to implement the *SLC*-40 zero suppression algorithm that is shown in the state transition diagram of Fig. 11. The counter state and the input data value are changed simultaneously by the transmit clock, thus the

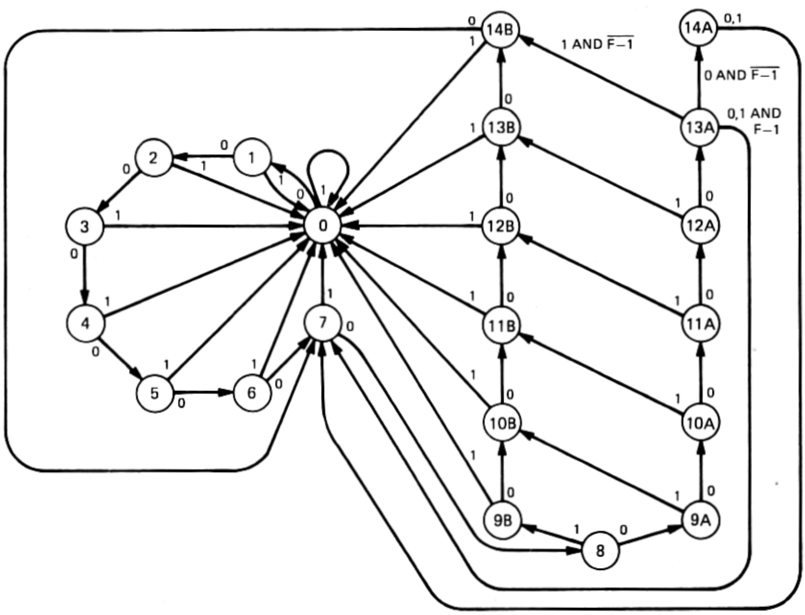

Fig. 11—State transition diagram for the *SLC*™-40 zero suppression algorithm.

state transitions shown are timed by the transmit clock. The next state is determined by the input data value, and the output data equals the input data unless a one is forced. The circuitry also "looks ahead" to prevent a forced one at the F-bit location in the frame. This is accomplished by detecting a frame bit time slot minus one pulse, F-1, when the zero suppression circuit is in state 13A. This forces a one at the next transition, and the correct frame bit is output in the following time slot.

4.2.5 Control of logic-signal-induced noise within the channel bank assembly

In a system realized with sequential logic like the *SLC*-40 system, logic load current flow is impulsive and consolidated at clock transition times. This current flow through the interconnect and power supply wiring can couple noise signals into other circuits.

To control this interference, a printed wiring board backplane is used to distribute logic signals and power to each row of channel units. The data bus and channel clock wiring is routed from the multiplexer to wire-wrap pins on each backplane over physically separated paths. This isolates the open-collector logic driven transmit data buses from crosstalk caused by the receive data buses and the channel unit clocks. Also, the multiplexer plug-in units are centrally located within the common units, thereby reducing the average length of the logic signal wires. This system configuration results in a readily manufacturable design with controlled noise characteristics, thus ensuring that the critical timing of the logic signals is maintained.

To reduce the transient current flow in the logic power wiring, and thus minimize radiation to adjacent circuitry, a heavy gauge pair of wires is utilized to connect the low voltage power unit to the individual backplanes. The multiplexer is powered through leads that are connected to the nearest backplane resulting in a minimum length logic signal return path between the multiplexer and the channel units. In addition, each plug-in unit contains a power supply decoupling capacitor, and the total effect of all these capacitors is to produce a distributed filter that eliminates the flow of high frequency currents on the power wiring.

4.2.6 Multiplexer/demultiplexer to digital line interface (including system maintenance function)

The line interface unit under control of the maintenance unit couples the multiplexer/demultiplexer and the line-feed power unit to either the main or the spare digital line. The maintenance unit selects the proper line through an algorithm that has as inputs the statuses of the digital line and the terminals. When a trouble condition persists, a two second clock advances the state of this algorithm in an attempt to restore the system to operation.

The current supplied by the line-feed power unit to the line interface unit is connected through a relay to center-taps on the line side of the transmit and the receive transformers. Normally, this current simplex powers the main digital line, but when the maintenance unit causes the relay to operate, the spare line is powered.

The transmit clock signal that the line interface generates causes the parallel-to-serial data converter in the multiplexer to output one new data bit of the serial bit stream for each clock pulse. The transmit clock also controls the conversion of this data into a bipolar code that the transmit transformer couples onto the powered digital line.

The line interface unit also equalizes and regenerates the low level bipolar signal on the receiving side of the digital line and converts this signal into TTL compatible positive and negative data rail unipolar signals. These signals, along with the recovered receive clock, are supplied to the demultiplexer which uses the two rail data to detect bipolar violations.

The maintenance unit integrates the bipolar violation data it receives from the demultiplexer. If errors occur at a sufficiently high rate or other trouble indicators exist for two seconds, the maintenance unit forces the line interface units to transfer system operation to the spare digital line. Data sent over the maintenance channel causes both terminals to switch at the same time. Should operation on the spare line not clear the trouble condition within two seconds, the RT line interface unit loops the receive digital signal back towards the COT. This loop-back test condition lasts for two seconds, then the maintenance unit returns the system to main digital line operation. The resulting "system out" state of the maintenance units causes a major alarm at the CO as the system is inoperative. The "system out" state also inhibits channel unit operation, thereby preventing false off-hook indications at the COT or ringing at the subscriber.

When the *SLC*-40 system is equipped with the most recent vintage maintenance units, a main or a spare digital line retry occurs once after either line fails. This retry allows the digital line four minutes to clear, which normally is sufficient if the trouble condition was caused by accidental contact with the line during work activity in the cable. The system does not continuously retry the main and the spare digital lines, as this would hamper trouble-shooting efforts on the defective digital line. Also, the resultant line powering transients might disturb other digital lines on the same cable route.

V. SUMMARY

The two large pair-gain digital carrier systems developed for the Bell System, first, the *SLM* system and, subsequently, the *SLC*-40 system, have proven that this kind of system can be operated successfully in the loop plant of operating telephone companies. Both systems have provided quality transmission and high reliability with low maintenance, while deferring or eliminating capital expenditures for cable, conduit and central office construction.

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