THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 57, No. 4, April 1978
Printed in U.S.A.

Loop Plant Electronics:

Analog Loop Carrier Systems

By T. N. RAO

(Manuscript received October 17, 1977)

Analog loop carrier systems have several distinct advantages which allow these systems to be economical even for as few as one to eight channels per cable pair. These advantages arise from their insensitivity to near-end and far-end crosstalk between cable pairs and the lack of complex common equipment at the terminals. Until recently, the analog systems have not benefited from the low hardware costs possible with the use of custom linear integrated circuits which can make the cost of companding, modulation, and demodulation inexpensive compared to the costs of powering and interface circuitry. Once this has been achieved as in the SLC™*-1 and* SLC™*-8 systems, the choice between digital and analog systems can no longer be based on hardware costs alone at full fill, but must also be based on such other differences as engineering and installation costs, flexibility, maintainability, and range of application.*

I. INTRODUCTION

The analog carrier systems used in the loop plant fall into two distinct groups: the single-channel systems that piggyback a carrier channel on top of an existing voice channel and the multichannel systems where four to eight voice channels are multiplexed onto a single pair of wires. The single-channel systems piggyback a carrier channel on top of an existing voice channel without disturbing the baseband channel in any appreciable manner. These systems are limited in their use to urban and suburban areas where no intermediate repeaters or pair conditioning, like removal of load coils, is necessary. In their range of application, they provide the most economic or frequently the most expeditious pair gain technique. The multichannel systems, on the other hand, tend to be used on longer routes with repeaters. These systems, because of having to deload the line for carrier frequency transmission and difficulties in handling baseband signals at the repeaters, do not attempt to preserve the normal baseband transmission on the wire pair and all channels are derived via carrier techniques. In both the single and multichannel systems double-sideband AM with transmitted carrier is popular for several reasons. Wideband FM,[1] even though practical for single-channel systems with some advantages over DSB-AM, has limited use for multichannel systems because of the large bandwidth requirements. The desirable compatibility between single and multichannel systems used in the same cable usually forces both systems to use the same or similar modulation technique and consequently wideband FM is not common for single channel systems. Narrowband FM does not have large bandwidth requirements but suffers from low noise immunity as compared to AM. SSB is very acceptable from the bandwidth point of view and, in addition, has several transmission advantages like insensitivity to phase distortions on the carrier line and decreased levels on the carrier line. However, at the present time, the greater complexity of the SSB modems as compared to DSB modems and the inability to use the extra channels possible in a given bandwidth due to the limited number of channels that can be powered from the central office without local power at the remote terminal, favors the DSB systems. DSB-AM systems, having their beginnings in the trunk plant, have in the loop plant progressed from the early vacuum tube versions through discrete transistor circuits to the integrated circuit version to be described in this paper. The single-channel *SLC*™-1 system will be described in some detail and followed by a less detailed description of the eight-channel *SLC*™-8 system which shares many of the integrated circuit techniques used in the *SLC*-1 system. The role of these analog systems in the loop plant can be inferred from the advantages they offer, which are outlined toward the end of the paper.

II. THE *SLC*-1 SINGLE-CHANNEL CARRIER SYSTEM

2.1 General description of operation

The simplicity of single-channel carrier systems which derive via carrier techniques an additional channel on an existing voice pair has long been recognized.[2,3] Over the years, they have progressed through vacuum tube and discrete transistor versions to the *SCL*-1 system which uses custom integrated circuits. This system, like all previous systems, basically consists of two modems: one at the central office (CO) and the other at the subscriber's premises. Figure 1 shows the system configuration which also shows a low-pass filter to prevent carrier frequencies from entering the physical customer's telephone. A carrier frequency of 76 kHz is used in the direction to the subscriber and 28 kHz in the opposite direction.

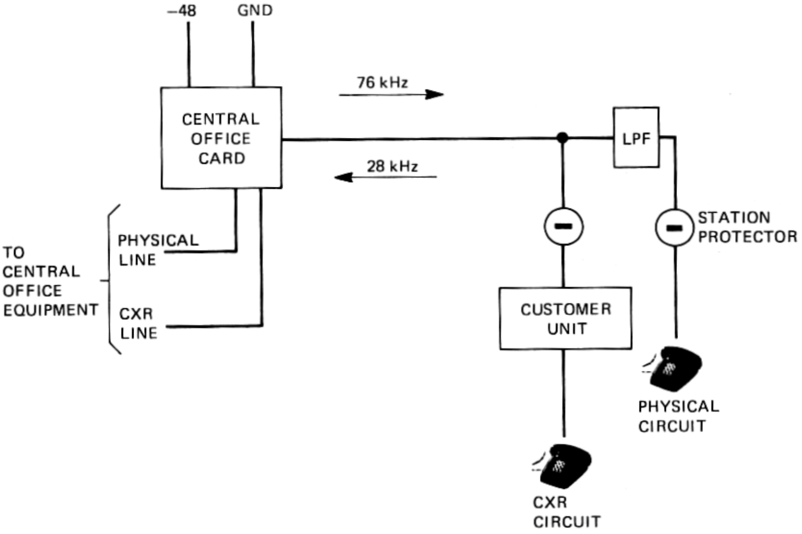

Fig. 1—*SLC*™-1 system configuration.

The block diagram of the CO modem is shown in Fig. 2. In the idle state no carriers are transmitted. When the derived customer goes off-hook the 28-kHz transmitter in the subscriber unit is turned on and the signal received at the CO modem is bandpass filtered, amplified, envelope detected and applied to the hybrid through an audio filter-amplifier combination. The output of the envelope detector also controls the loop

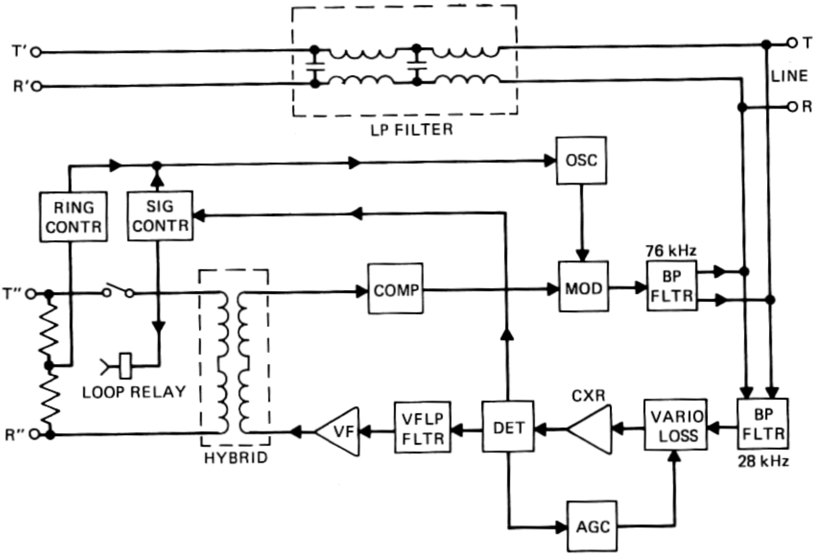

Fig. 2—*SLC*™-1 CO modem.

relay which repeats loop closure and dial pulses. *TOUCH-TONE®* calling signals are transmitted just as speech signals. The CO transmitter is turned on either by the received 28 kHz, so that it can return dial tone, or by a ringing signal applied to the modem by the CO equipment. The ringing signal gates the transmitter on and off at the 20-Hz rate. Audio signals are compressed by a syllabic compressor before being applied to the transmitter.

In the subscriber terminal, shown in block form in Fig. 3, modulation and demodulation are similar to the CO modem except for interchange of transmit and receive frequencies and the syllabic expandor in the receive path. The 28-kHz signal transmitted by the subscriber unit is level controlled by the received 76-kHz signal so that carrier signals received by the CO modems tend to be at the same level and unequal level crosstalk problems are minimized. When the phone is on-hook, 20-Hz modulation on the received 76-kHz carrier activates the ringing generator circuit which applies ringing to the phone. The electronics and the telephone at the subscriber end are powered by a six-cell rechargeable nickel-cadmium battery. During the idle states of the physical and derived telephones, the battery is charged by a dc-to-dc converter that draws about 3 mA from the line. The physical arrangements of the CO and subscriber terminals are described in a companion paper.[4]

Custom linear integrated circuits are used in the CO and subscriber modems. These integrated circuits have made possible for the first time the use of a high performance syllabic compandor that meets trunk carrier objectives. The compandor, which is used only in the high fre-

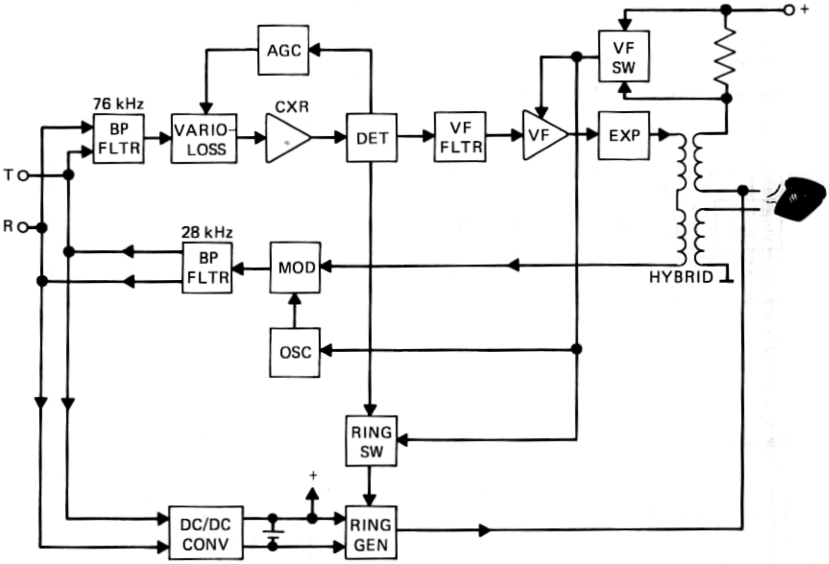

Fig. 3—*SLC*™-1 subscriber modem.

quency direction, allows lower receive levels, permitting a range of 18 kft on any nonloaded resistance designed loop without excessive bridge taps. Among other benefits that arise from the use of silicon integrated circuits, which can accommodate complex circuitry on a single SIC, are low signal distortion without sacrificing signaling speeds, close control of channel loss and wide operating temperature range. Each of the modems uses four silicon integrated circuits. The transmitter, receiver, and compressor or expandor functions are provided by one chip each, the control and miscellaneous functions are built into the fourth chip. Since the control functions are different at each end, a total of five silicon integrated circuit designs are used.

2.2 Circuit description

2.2.1 Receiver

The receiver performs the functions of automatic gain control, envelope direction, audio filtering and amplification. It also detects the presence of the carrier signal to generate control signals for ringing or loop closure, and provides cross-control current for the transmitter. All of the above receiver functions are incorporated into one IC chip. The functional schematic diagram for the receiver circuit is shown in Fig. 4. The input signal is fed to a balanced variolosser which is followed by a balanced-input carrier frequency amplifier. The amplified signal goes through an envelope detector, which consists of a high-gain amplifier

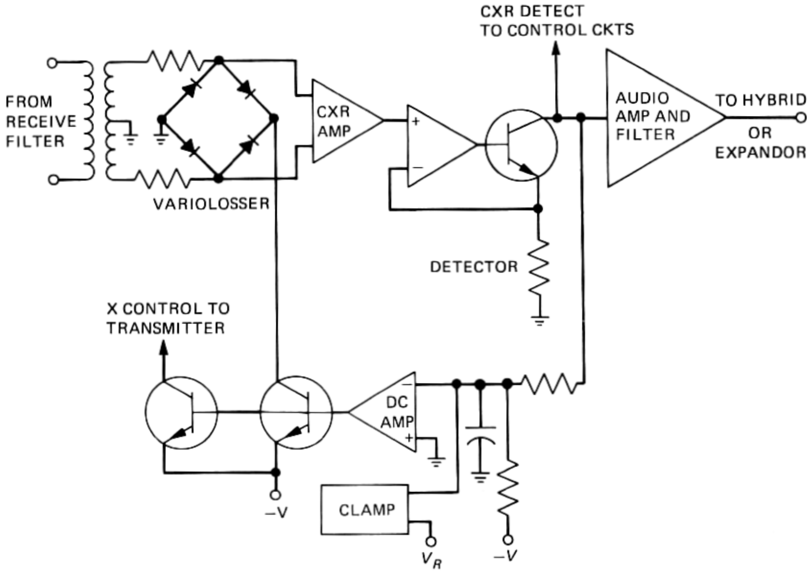

Fig. 4—Receiver circuit.

with a transistor in the feedback that acts as a rectifier. The V_{be} of the rectifying transistor is absorbed in the high loop-gain; therefore the current in the collector of the transistor is a precise half-wave rectified version of the input signal. The carrier component of the detected signal is filtered by a third-order active filter, which also acts as an amplifier and driver for the hybrid, and the demodulated audio appears at the output. For automatic gain control (AGC), the dc component of the rectified signal is applied to a high-gain dc amplifier, the output of which controls the current in the variolosser diodes.

Through the use of a custom-designed IC, it has been possible to achieve high performance economically. For example, the AGC holds the audio output to within ±0.2 dB for about 55 dB of carrier level variation at the input. Thanks to a precise detector and high loop gain, the audio output level, for a given modulation index, is determined primarily by a few discrete resistors, hence resulting in excellent temperature stability. The receiver also features low harmonic distortion, about 40 dB down for 50 percent modulation at 1 kHz. The capacitor that precedes the dc amplifier affects both the response time of the AGC and audio harmonic distortion. One has to choose a large capacitor to reduce the amount of the residual audio signal in the variolosser control current, which would produce second harmonic distortion in the audio signal. However, this would also slow down the AGC response time. The problem has been resolved by using a clamp circuit which in the absence of a carrier signal holds the input to the dc amplifier close to its steady-state value (just above ground), hence reduces the AGC response time considerably.

The same receiver chip is used in both the central office and the remote terminal units. To minimize the battery drain in the remote terminal unit, in the idle condition when the telephone set is on-hook, the audio portion of the receiver circuit is kept off, and the receiver draws only 900 μA from the battery.

2.2.2 Compandor

The compandor used in the high-frequency direction is a 2:1 syllabic compandor, which reduces the probability of crosstalk interference. Together with a wide AGC range, the compandor extends the transmission range to 53 dB of loss at 76 kHz, and hence covers essentially all nonloaded loop plant.

The compandor uses a new design, which represents a marked departure from prior art in its implementation. Both the compressor and the expandor use the same custom-designed IC chip. Each circuit consists of one IC chip and several discrete resistors and capacitors. The functional block diagram is shown in Fig. 5. The high gain of the operational amplifier and negative feedback force the output signal of the two differential pairs to be of the same amplitude and opposite phase (input

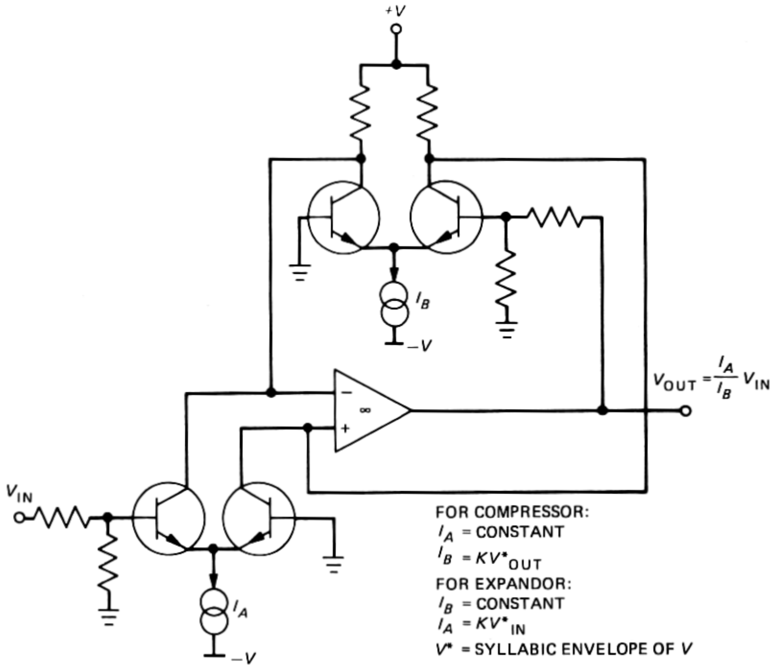

Fig. 5—Compandor circuit.

of the operational amplifier to be zero), hence it can easily be shown that

$$V_{OUT} = \frac{I_A}{I_B} V_{IN} \tag{1}$$

For the compressor circuit I_A is a constant dc, and I_B is proportional to the syllabic envelope of V_{OUT}, which is obtained by rectifying and filtering the output signal. For the expandor, I_B is a constant dc and I_A is made proportional to the syllabic envelope of V_{IN}.

This circuit arrangement offers several novel features. First, the gain of the circuit is essentially temperature independent, since the temperature dependent factor in the gain of the feedback differential pair is canceled by an identical factor in the differential pair which is the forward path. For 100°C change in temperature (−40°C to +60°C), the output variation is about ±0.1 dB. This is of particular importance in the loop plant where the customer equipment can be expected to undergo wide temperature variations. Also, the circuit of Fig. 5 relies on the gain of differential pairs which is well defined in terms of the currents I_A and I_B. The gain of this circuit is essentially determined by discrete resistors. This results in very stable compressor and expandor characteristics and excellent compandor tracking (less than ±0.2 dB over 70-dB range). In contrast, conventional designs employ the temperature dependent ac impedance of diodes for variolossers. Moreover, the ac impedance of diodes as a function of the dc control current is not so well characterized[5] and is a variable from one unit to another.

The subjective testing of the compandor has revealed no noticeable degradation in the speech quality, or the hush-hush effect, sometimes associated with compandors. It offers about 28 dB of effective compandor advantage (in the presence of speech). The performance of this compandor well exceeds the recommendation of CCITT[6] for trunks. High performance in syllabic compandors used in loop carrier systems is most desirable, since they can be in cascade with other syllabic compandors in the telephone network.

2.2.3 Transmitter

A simplified schematic diagram of the transmitter is shown in Fig. 6. It consists of a carrier frequency LC oscillator and a differential pair modulator. The current I_1 is dc with the audio modulating signal superimposed on it. Through the use of an operational amplifier and discrete resistors, the modulation index (ratio of the ac to dc component in I_1) is set with great accuracy. Also, because of the high loop gain of the operational amplifier, the current I_1 is essentially free of harmonics of the modulating audio input, even for modulation levels approaching 100 percent. The modulator, which consists of the differential pair Q_1, Q_2, can be used either as a linear or switching modulator, by grounding pins

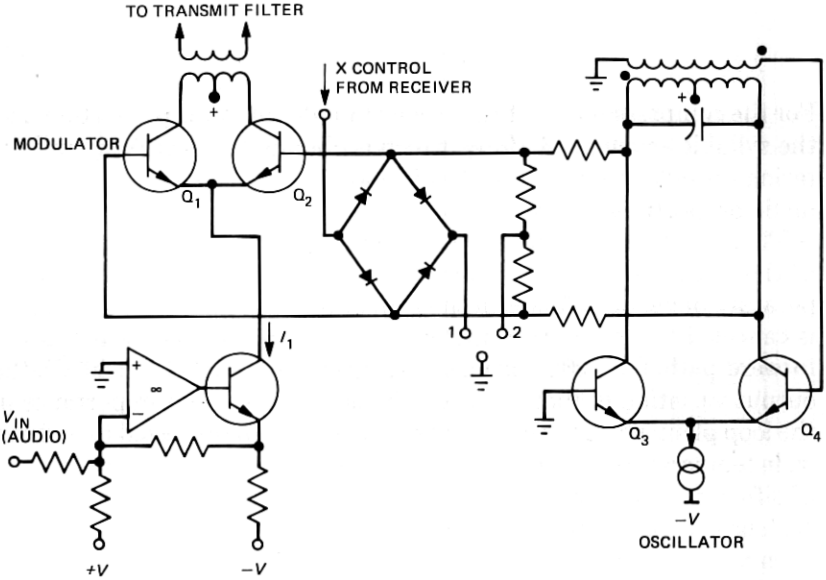

Fig. 6—Transmitter circuit.

1 or 2, respectively. In the remote terminal unit, where the cross-control function is necessary, the modulator is used in its linear mode. The cross-control current from the receiver controls the ac impedance of the diode bridge, and hence the carrier level at the bases of Q_1, Q_2 and the output level of the transmitter, without affecting the modulation index. The diode bridge also conveniently serves to cancel the gain variation of Q_1, Q_2 due to temperature, and to reduce carrier frequency distortion, by predistorting the signal. In the central office unit, where the output level of the transmitter is to remain constant, the modulator is used in the switching mode. In this condition the diode bridge is not conducting, and there is sufficient carrier signal at the bases of Q_1 and Q_2 to switch the current I_1 back and forth between Q_1 and Q_2.

The oscillator circuit uses a differential pair gain stage, where the output is transformer-coupled to the input, in the positive feedback sense. The swing at the base of Q_4 is of sufficient magnitude to switch the current I_2 completely between Q_3 and Q_4. Hence, the collector currents of Q_3 and Q_4 are square waves, which after being filtered by the LC tank produce sinusoidal voltage at the collectors. The amplitude of the oscillation is determined mainly by I_2 and the load resistance across the collectors, and can be set accurately. The frequency stability is determined almost entirely by the LC product and the active circuit has negligible effect on it.

The entire transmitter circuit is incorporated in one IC chip, and the same chip is used both in the central office and the remote terminal units. In summary, the transmitter exhibits good level and frequency stability, linearity, and accurate modulation index. It operates satisfactorily from −40°C to +60°C.

2.2.4 Ringing generator

For ringing, the 20-Hz ringing signal is detected in the central office unit and the 76-kHz transmitter is turned on and off at 20-Hz rate. At the remote terminal receiver the envelope of the incoming carrier is detected, and the resulting 20-Hz signal is applied to the ringing generator. A simplified functional block diagram of the ringing generator is shown in Fig. 7.

The 20-Hz ringing signal from the receiver is used to turn a 50-kHz oscillator on and off. The resulting 50-kHz pulse train, which is modulated by the ringing signal, is up-converted by the switching transistor Q_2 and the transformer. The output of the transformer, which is a high voltage 50-kHz signal, is envelope detected by the diode CR1 and the capacitor. Hence, the voltage across the capacitor is a high voltage 20-Hz square wave capable of ringing the phone. During the half-cycle that the voltage across the capacitor is high, the ringing current flows through the forward biased zener CR3, the ringer in the phone, and back through

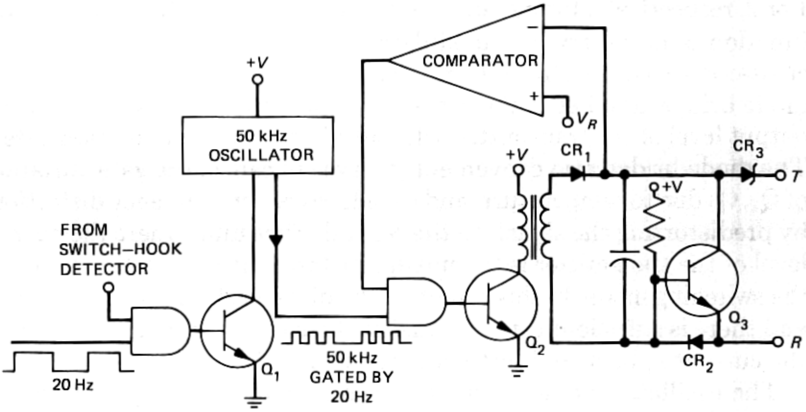

Fig. 7—Ringing generator circuit.

the forward biased diode CR2, which keeps Q_3 off. In the low half-cycle, the current flows back through the reverse biased zener CR3, and the transistor Q_3, which is saturated in this condition and provides a low impedance path. A high voltage reverse biased diode, not shown in the diagram, isolates the ringing signal from the switch-hook detector circuit. The ringing voltage is regulated by gating off the input to the up-converter as soon as the output voltage exceeds a reference level V_R. In the off-hook condition the ringing generator is inhibited by the gate preceding Q_1.

This ringing scheme has several advantages. First, by using a high frequency up-converter it avoids bulky 20-Hz transformers. Also, since the 20-Hz switching is done on the low-voltage side of the converter, only one high voltage transistor is necessary. The ringing generator can ring at least three phones, over a temperature range of −40°C to +60°C.

All of the components in Fig. 7 to the left of Q_2, plus the control functions and part of the battery charger, are incorporated into one IC chip.

2.2.5 The battery charger

The battery, which consists of six nickel-cadmium cells, is trickle-charged from the line. The battery charger shown in Fig. 8 draws a small dc current from the line (about 3 mA), and through the use of a simple and efficient switching type converter, charges the battery at a much higher rate.

The input resistors prevent the dc loading of the line, and the diode bridge guards against tip and ring reversal. The oscillator produces a current pulse train, which drives the switching transistor Q_1 on and off into saturation. During the interval that Q_1 is saturated, current drawn from the line builds up in the inductor. When the transistor is turned

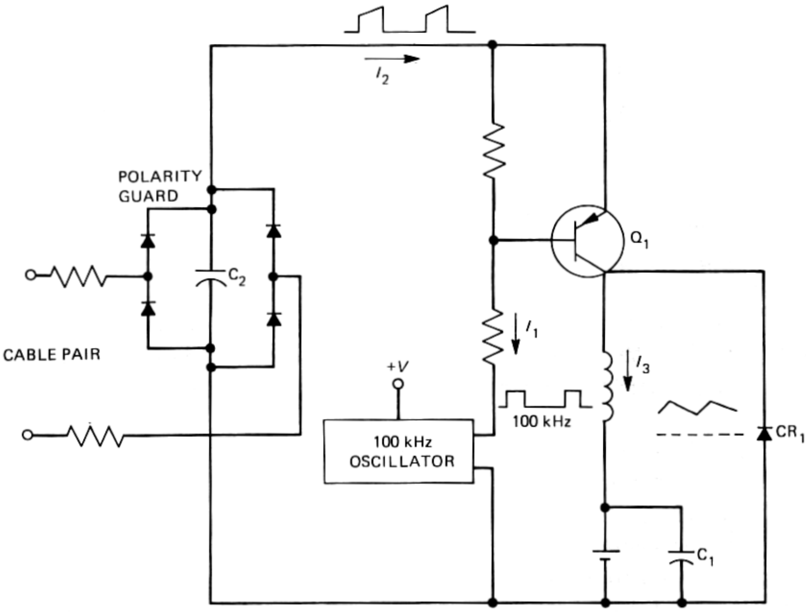

Fig. 8—*SLC*™-1 battery charger circuit.

off, current continues to flow in the inductor through the diode CR1 at a decreasing rate. Hence, the battery is charged during both intervals. The ac component of the current I_2 is filtered by the capacitor C_2, and its average dc component is drawn from the line. Note that the battery is charged approximately at the peak rate of I_2, which is much larger than its average value drawn from the line. The ratio of the charging current to the line current is determined by the duty cycle of the oscillator.

2.2.6 Testing compatible remote terminal

The current drawn by the battery charger makes the physical pair look leaky when tested for leakage between the conductors. When the normal *SLC*-1 system is used with ESS offices, the leakage tests performed prior to call completion can indicate excessive leakage and the call might not be completed. In addition, routine insulation tests from an automatic line insulation test set or from a test desk do not provide very useful information on the condition of the cable pair. To overcome these problems a test compatible subscriber unit has been developed. In this version the battery charger senses the onset of a test on the cable pair and disconnects the battery charger from the line for a period of about ten seconds. During this time interval, the subscriber unit looks like a high resistance, greater than 800 kΩ, and useful information on leakage between the conductors can be obtained.

III. THE *SLC*-8 MULTICHANNEL CARRIER SYSTEM

3.1 General system description

Analog multichannel carrier systems, like single channel systems having their beginning in the trunk plant, were first used in the subscriber plant in the 1950s. The type-P carrier system[7] designed for the loop plant provided, via DSB-AM techniques, four channels on a single pair of wires. Even though the circuits used transistors, a variety of technological problems made it too expensive except for use on very long rural loops. In the 1960s several manufacturers introduced multichannel analog carrier systems that have been more economical to use. The *SLC*-8 system represents another large step in the evolution of these systems, since the reliability, performance and economies made possible by the use of custom linear integrated circuits are exploited for the first time.

The *SLC*-8 system uses one pair of wires to derive eight voice channels. The frequency allocation is shown in Fig. 9, which is essentially the same as the REA allocation to allow for the coexistence of *SLC*-8 system with other analog systems in the same cable. The CO terminal consists of eight modems and a common circuit pack. The common circuit pack has, in addition to all the circuits necessary to interface the modems with the carrier line, a −48 V to ±135 V dc/dc converter that powers the remote terminal and the repeaters. The ±135 Vdc is applied to the line in a metallic mode along with the multiplexed signals. Repeaters using directional filters are used along the carrier line at approximately four-mile intervals on 22-gauge cable. Any combination of wire gauges is allowed in a repeater span and the spacing should correspond to 35 dB of loss at 112 kHz, which is a generally accepted standard for analog loop carrier systems. The remote terminal arrangement can be one of two types. The "lumped" arrangement shown in Fig. 10 has a remote terminal consisting of eight modems and a common power converter that draws power from the line and provides all the required dc voltages for the modems. The other type is the "distributed" arrangement shown in Fig. 11 where there are as many as eight separate remote terminals each housing a modem and a power supply. The distributed system allows the use of the system on very sparsely populated routes since a remote terminal can be connected to the carrier line anywhere along its whole length. In both the

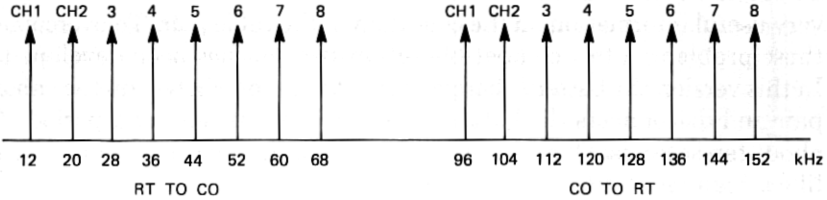

Fig. 9—Frequency allocation for *SLC*™-8 system.

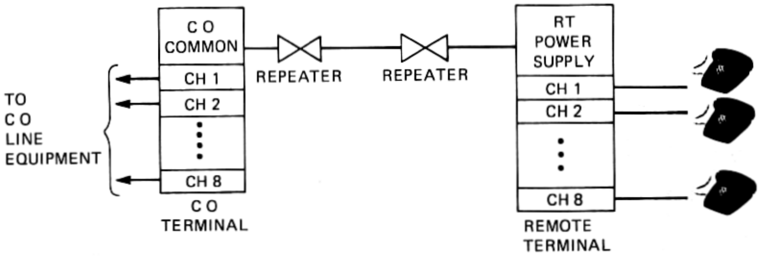

Fig. 10—Lumped *SLC*™-8 system.

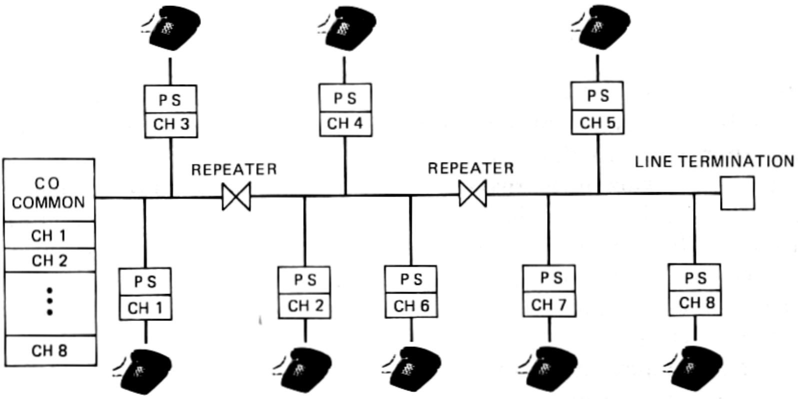

Fig. 11—Distributed *SLC*™-8 system.

lumped and distributed systems the repeaters and remote terminals are completely powered from the CO up to a maximum carrier line resistance of 2400 ohms. This resistance limit corresponds to approximately 28 miles on 19 gauge and 14 miles on 22 gauge from the CO. For the very few routes that are longer than this allowable conductor resistance, other methods of powering, such as remote ac power with battery backup or a parallel pair for additional dc power from the CO, must be provided.

3.2 Principles of operation

The block diagram of the CO modem is shown in Fig. 12. The similarity of this block diagram to that of the *SLC*-1 CO modem shown in Fig. 2 is obvious. The basic difference is that the CO to RT carriers are always on and ringing information is transmitted to the RT by modulating the carrier with a 2-kHz tone that is gated at the 20-Hz CO ringing frequency. Also, the receiver works into an expandor instead of directly driving the CO line equipment, since companding is used in both directions of transmission. The single-party CO modem uses four custom integrated circuits, one each for the receiver, expandor, compressor and the com-

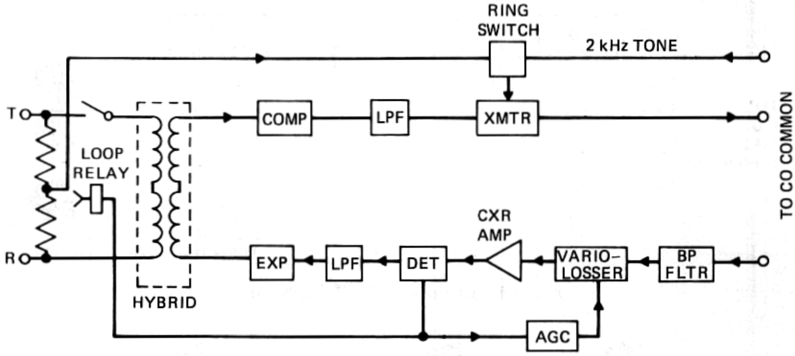

Fig. 12—*SLC*™-8 single-party CO modem.

bined functions of transmitting and controls. The transmitter and controls circuit is the only one specifically designed for the *SLC*-8 system; the other three are identical to the ones used in the *SLC*-1 system. Differences in levels in the two systems are accommodated by changes in the values of discrete resistors and capacitors external to the integrated circuits. The multiparty modems use an additional integrated circuit to perform the more complex control functions necessary for both two-party ANI (Automatic Number Identification) and four-party fully selective services.

The frequency allocation in Fig. 9 allows the use of a common band-pass filter to eliminate harmonics of all carriers for the high group as shown in the block schematic of the common circuit pack in Fig. 13. The low group signals received from the line are low pass filtered, preamplified and distributed to the modem cards. The common circuitry also contains the 2-kHz audio tone generator which is used by all the modems

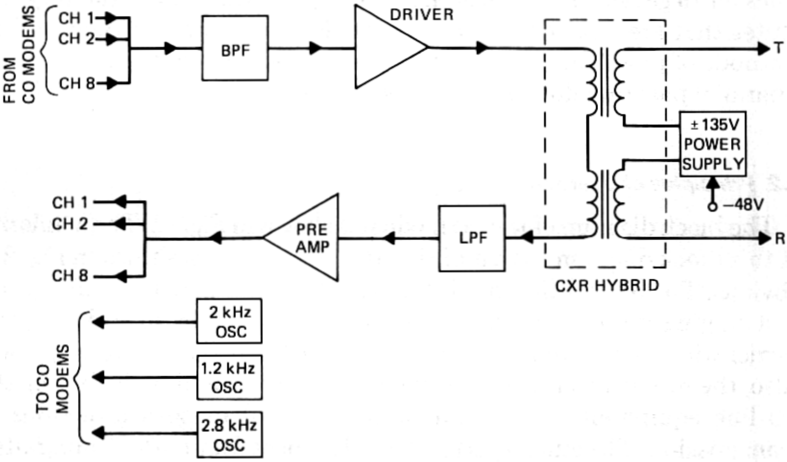

Fig. 13—*SLC*™-8 CO common circuit.

to transmit ringing information, as mentioned earlier. For multiparty service the ringing information as to whether the tip or ring party is to be rung is indicated by the presence or absence of a 2.8-kHz tone and the information as to whether it is positive or negative superimposed, by the presence or absence of a 1.2-kHz tone. These 2.8-kHz and 1.2-kHz tone oscillators, which are utilized only by the multiparty modem cards, are also included in the common card. The −48 V to ±135 V dc/dc converter is a switching type operating at a frequency of 82 kHz, which is exactly the center of the low and high groups to minimize interference problems. The circuitry needed to regulate this supply and provide short circuit protection is built into a custom integrated circuit. The same integrated circuit is also used in the repeater and remote terminal power supplies.

The single party modems used in the lumped and distributed remote terminals are identical; a block diagram is shown in Fig. 14. The differences between this modem and the *SLC*-1 subscriber modem shown in Fig. 3 are the added compressor in the transmit path and the way ringing is generated. Ringing voltage is obtained by chopping the 180 Vdc provided by the power supply card at a 20-Hz rate. The 20-Hz signal is obtained from the received gated 2 kHz on the carrier so that the ringing frequency is exactly the same as at the CO. These modems use a total of five linear integrated circuits, one each for the receiver, expandor, compressor, transmitter and controls. The transmitter, compressor, and expandor circuits are the same as the ones used in *SLC*-1, the receiver is very similar to the one in *SLC*-1, but the controls circuit is specifically designed for *SLC*-8. As in the multiparty CO modem, an additional integrated circuit is used for multiparty control functions.

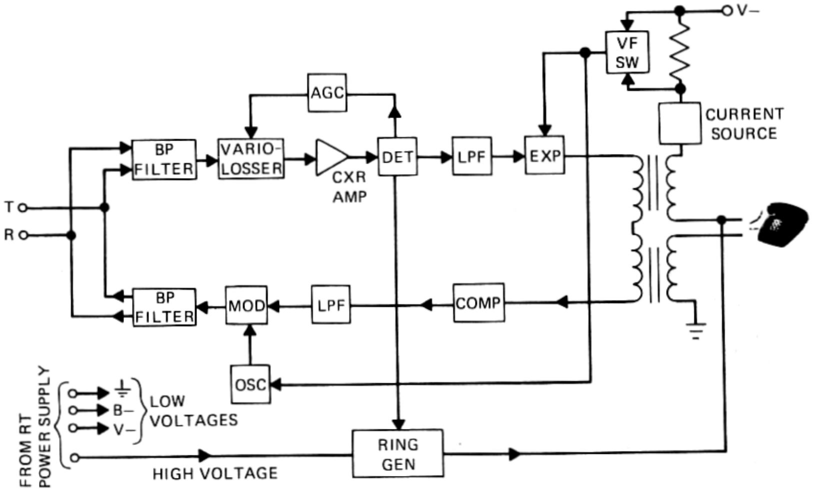

Fig. 14—*SLC*™-8 single-party RT modem.

The common power supply used in the lumped remote terminal is shown in block form in Fig. 15. The ±135 Vdc on the carrier line is fed into two dc/dc converters through a low-pass filter and a polarity guard. One of the converters provides 180 Vdc to the modems for conversion into ringing signals when needed. The other converter provides required voltages for the modem circuits and approximately 16 volts for powering the telephone sets. Like the CO converter, these converters are also switching-type operating at 82 kHz. The power supply in the distributed remote terminal has only one dc/dc converter that provides all the required voltages to the modem. The converters in both the lumped and distributed terminals use the same integrated circuit as in the CO converter for control.

The functional diagram of the repeater is shown in Fig. 16. The high group signals from the CO direction are passed through the high-pass filter level adjusted by a variolosser and preamplifier combination. The shaping network shapes the signals so as to compensate for a nominal repeater span. The shaping is a compromise for all possible gauges. The line driver drives the line through another high pass filter. The variolosser is controlled by the output of the line driver so that the high group output on the field side of the repeater is similar to the levels originating at the CO. The low group side of the repeater is similar to the high group side except that the variolosser in this direction is controlled by the same control current as in the high group variolosser to preequalize for the

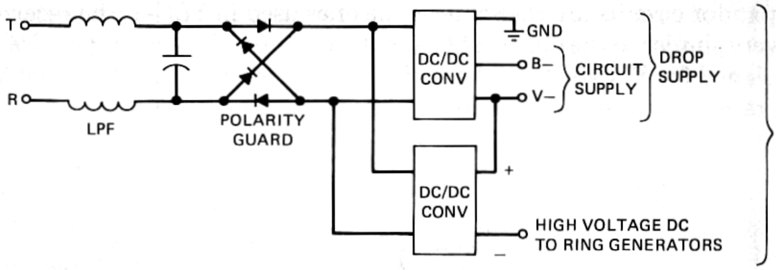

Fig. 15—RT common power supply.

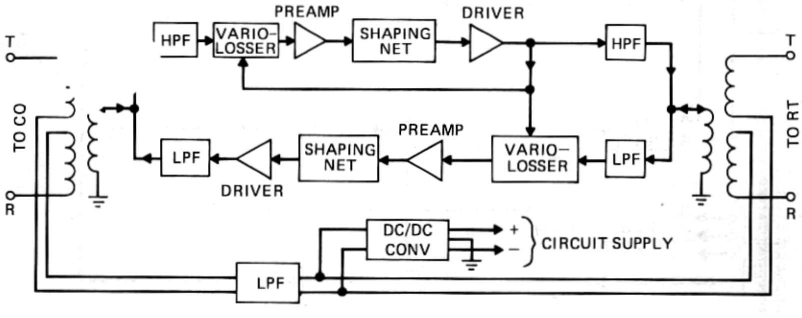

Fig. 16—*SLC*™-8 repeater.

repeater section on the CO side of the repeater. The directional filters are conventional LC filters. The loss requirements of these filters are determined not just by the stability requirement of the repeater but also by the required stability of the gain shape in each direction and inherent noise in the input stages of the preamplifiers. The filters introduce some nonlinear phase shifts in the carrier channels close to the cut-apart region. These nonlinear phase shifts result in linear and nonlinear distortions in the baseband signal and cannot be allowed to accumulate over many repeaters. Phase equalization in cascade with each repeater is used when the total number of repeaters used on a carrier line is more than three, and all eight baseband channels have to meet the standard transmission objectives for frequency response.

The repeater uses a total of five integrated circuits, one in the power supply that converts the ±135 volts on the line to the voltages needed for the circuit, one for gain control and preamplification in each direction and two line drivers. The integrated circuits used in each direction of transmission are the same types but use different external components.

IV. ADVANTAGES OF ANALOG CARRIER SYSTEMS IN THE LOOP PLANT

All the advantages of analog carrier systems which fall into the broad categories of ease of engineering and installation, flexibility, and simple maintenance arise from the low bandwidths needed for transmission, absence of complex common equipment, ability to use one pair of wires for both directions of transmission and the availability of a high performance syllabic compandor.

The impairments to carrier systems caused by crosstalk between cable pairs can be very effectively circumvented by analog carrier systems. The low bandwidth requirements of these systems allows the use of two separate bands of frequencies for the two directions of transmission without serious increase in the cable loss which not only makes these systems immune to NEXT but also makes operation on a single pair of wires possible. The other significant crosstalk, FEXT, is overcome by the use of syllabic compandors. It has been shown[8] that a compandored DSB analog carrier system when installed, even in small 25-pair cables with no pair selection, has insignificant intelligible crosstalk problems due to FEXT. This insensitivity to the two major crosstalk mechanisms in twisted pair cable gives rise to wide repeater spacings (approximately four miles on 22 gauge) and very simple carrier line engineering. Once the bridge taps and load coils are removed, the repeaters are located at 35 dB loss at 112 kHz as computed from cable records. Field measurements of loss at repeater locations are made basically to locate unrecorded bridge taps or load coils. Because of the wide repeater spacings few long routes need more than three repeaters, two being the average. This minimization of the number of repeaters in a system decreases the number of repeater sites along a route even if there are many systems used along a route.

Installation of these systems is greatly simplified by the lack of complex common circuitry and interconnection within a terminal. Common circuitry is essentially limited to power supplies and is built into the system. Each CO terminal has its own ±135V line supply and each terminal, which occupies only half a shelf,[4] needs only -48V from the CO which is fed through a dedicated fuse in a fuse and alarm panel. The CO installation, therefore, essentially consists of mounting the shelf, connecting -48 volts, and cabling the carrier line and demultiplexed channels to the main distribution frame.

The plug-in repeaters used along the carrier line have no field adjustments just as all other parts of the system. The remote terminals, lumped or distributed, are completely powered from the CO up to a cable resistance of 2400 ohms, a particularly important advantage where power distribution is subject to long outages. Most applications on long routes fall within this resistance limit. This powering capability comes from several reasons. One is that an eight-channel system can be located nearer to the customers being served without any significant system fill problems and this decreases the power needed for the telephones. The second reason is that the multiplexing and demultiplexing operations are done by passive LC filters which need no power. Complete CO powering of these systems is a definite advantage since no coordination of installation activities with the power company is needed. Standby batteries for powering the system during power outages, which are generally considered as high maintenance items are also eliminated.

The minimal engineering and installation effort needed for these systems provide flexibility: a decrease in planning interval needed allows rapid response to service requests and growth by small increments, a system at a time or even a channel at a time, which decreases initial investment and takes out the risks generally inherent in growth forecasts. Temporary applications, even in urban areas, are encouraged since in most cases fewer than three repeaters are used and it is relatively easy to remove a system from service and reuse it on another route.

Since the only significant common equipment in a terminal are power supplies, the reliability of analog carrier should in principle be excellent. The lack of complex organization greatly simplifies troubleshooting and craft training.

V. THE FUTURE OF ANALOG CARRIER IN THE LOOP PLANT

The single-channel carrier system described can be installed and removed with very little craft training and practically no disruption of service to the existing service on the physical wire pair. Any time-domain multiplexing technique to allow the transmission of two channels on a wire pair requires modulation of both channels. This essentially involves two sets of electronics as opposed to one set of electronics for a frequency division system that preserves baseband transmission. Hence, the cost advantage of these analog single-channel systems is likely to continue for a long time.

In case of the multichannel system the ease of engineering, installation, and maintenance, for reasons given earlier, are hard to surpass. The seemingly small number of channels, eight, on a pair of wires gives about the same pair gain ratio as the larger digital systems that need four pairs of lines including spare carrier lines. It is interesting to note that even though it is possible to increase the number of channels from eight by increasing the bandwidth on the carrier line, or going to a single sideband system, it is in most cases undesirable for several reasons. The ability to power the repeatered line, remote terminal and the standard telephones at a given ohmic distance from the CO vanishes as the number of channels is increased and the need for a spare repeatered line can arise, resulting in a loss of some of the important advantages of these systems. From these general arguments it appears that the number of channels per system is not likely to be increased in future designs.

The basic analog carrier channel can provide better than 10 dBrnc noise performance and is transparent to most voice band data signals. The extension of integrated circuit technology to analog systems as it has been done in the *SLC*-1 and *SLC*-8 systems has eroded the cost differences between analog and digital modems which provided the original impetus for digital systems. Further developments such as the use of mechanical filters and low-power phase-locked loop techniques can benefit these systems even more and their attractiveness will continue as long as there is a demand for small cross-section systems, or a need to work between an analog local office and a standard telephone set.

VI. ACKNOWLEDGMENTS

The author, as it frequently happens while reporting on significant development projects, is just the scribe singled out of a group of people, and of the large group of people responsible for the development of *SLC*-1 and *SLC*-8 systems acknowledges the contributions of P. P. Bohn, B. S. Bosik, J. H. Derby, D. E. Stone, R. Toumani, F. P. Tuhy, Jr., and T. G. Wilson, Jr., to the system and circuit designs reported in this paper.

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