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Loop Plant Electronics:

Voice Frequency Electronics for Loop Applications

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Over the past 100 years the telephone loop connecting central office switching equipment and the telephone customer's premises has evolved from aerial open wire to buried plastic-insulated twisted pairs. In the last 20 years the use of electronic circuits for range extension has become popular. These circuits allow use of higher resistance loops (finer gauge wires) than central offices are normally designed to accept. This paper reviews some of this history, describes rural and suburban systems of voice frequency range extension, presents requirements and circuit design considerations, and compares several electronic range extender circuits currently used to implement these systems.

I. GENERAL

The term voice frequency loop electronics refers to a family of equipment, usually central-office-mounted, intended to aid the operation of subscriber loops having much higher resistance than provided for in standard switching equipment designs of the past. This allows telephone companies to reduce outside plant expenditures through the use of cable of finer gauge than might otherwise be used. Such circuits are generally referred to as range extenders or loop extenders, indicating the function of extending central office loop resistance range by aiding signaling, supervision, and transmission functions. The use of such circuits dedicated to individual loops is particularly appropriate in rural areas where cable routes of 5 to 20 miles in length are common. By integrating range extension capability into the switching system, so that several lines share a single range extender, voice frequency loop electronics can be economically applied in many suburban areas, as well.

These loop designs allow relatively simple prescription of electronic treatment for high-resistance residential facilities. They do not in general apply to special business services like PBX trunks or to coin station lines of high resistance. These latter facilities usually require engineering design attention to satisfy precision loss or complex signaling requirements.

This article gives some of the history of voice frequency loop electronics in the Bell System, reviews rural and suburban range extension systems, outlines the requirements that range extenders must satisfy, and describes in detail some Bell System circuits tailored to the rural and suburban loop environments.

II. HISTORY OF VOICE FREQUENCY LOOP ELECTRONICS

2.1 Rural areas

Within a few years of the invention of the telephone, the open wire pair became the dominant medium for telephone transmission. The rapid growth of telephone demand in urban areas quickly caused the problem of open wire congestion in cities, fostering the development of cables. Improvements in relay sensitivity and cable insulation made it possible to use cable finer than the original 18 gauge that was intended for universal use. The high cost of copper encouraged the use of 22 gauge, 24 gauge, and finally 26 gauge cable as early as the 1920s in the cities.[1] A four gauge family (including 19 gauge) is almost universal in loop applications to this day, although aluminum cables have been used to a small extent in recent years. The trend toward finer gauges is illustrated in Fig. 1.

In rural areas demand for telephone service generally lagged behind that in urban areas until well after World War II with open wire continuing to be used widely as the principal loop transmission medium. Open wire with its low resistance and low capacitance per unit length has been a very efficient loop facility not ordinarily requiring range extension. In the 1950s increased rural demand for service coincided with the introduction of polyethylene insulation offering the prospect of water-resistant wire and cable needed to obtain low maintenance costs on long cable routes.[2] As cables and plastic-insulated wire began to replace open wire, it became apparent that even 19 gauge copper wire, the coarsest gauge commonly available in cable, limited signaling, supervisory, and transmission range of existing central offices to a maximum distance of 50,000 to 80,000 feet depending on the vintage of switching equipment. To serve longer loops required the continued use of open wire.

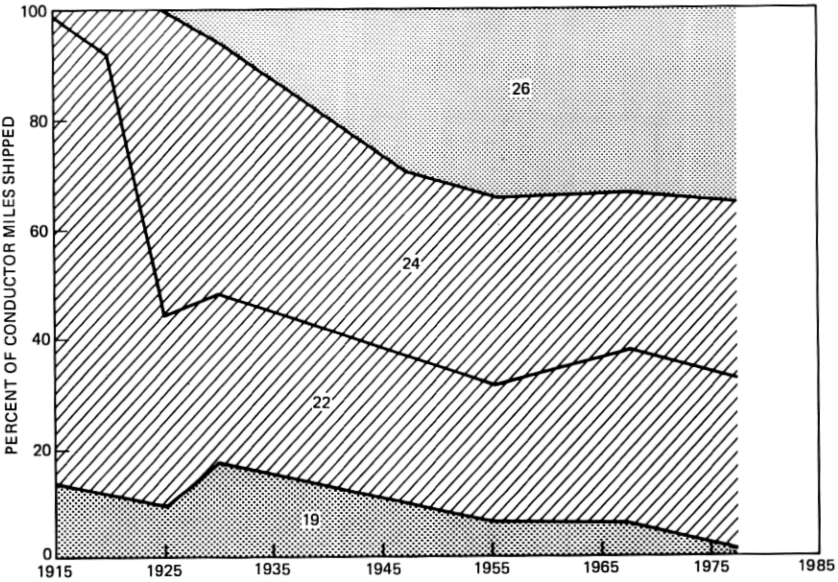

Fig. 1—Recent shipments of exchange cable by Western Electric by cable gauge.

To be able to remove open wire altogether, it was necessary to improve central office switching system performance, first by increasing the sensitivity of relays that sense the state of the telephone switch-hook on originating calls and terminating calls and during dial pulsing. Rather than overhaul an entire switching system, sensitive circuits called "dial long lines" (DLL) were interposed between the loop termination on the main distributing frame and the central office line equipment as required. These DLL circuits incorporated repeat coil transformer isolation between loop and central office equipment. Relay designs, generally more sensitive (and more expensive) than those in the switching system were used to sense telephone set switch-hook states. The DLL supplied dc voltage for supervisory, signaling, and talking current. This voltage was usually higher than the normal 48-V central office battery voltage. Figure 2 is a block diagram that illustrates this principle. Most step-by-step switching systems, No. 1 ESS and some No. 5 crossbar systems can signal and supervise to a maximum conductor loop resistance* of

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* Conductor loop resistance includes an allowance for central office wiring and station drop wire as well as the resistance of the outside plant cable from the central office to the drop wire terminal. Total loop resistance is the conductor loop resistance plus the resistance of station equipment and wiring (usually 200 ohms or less).

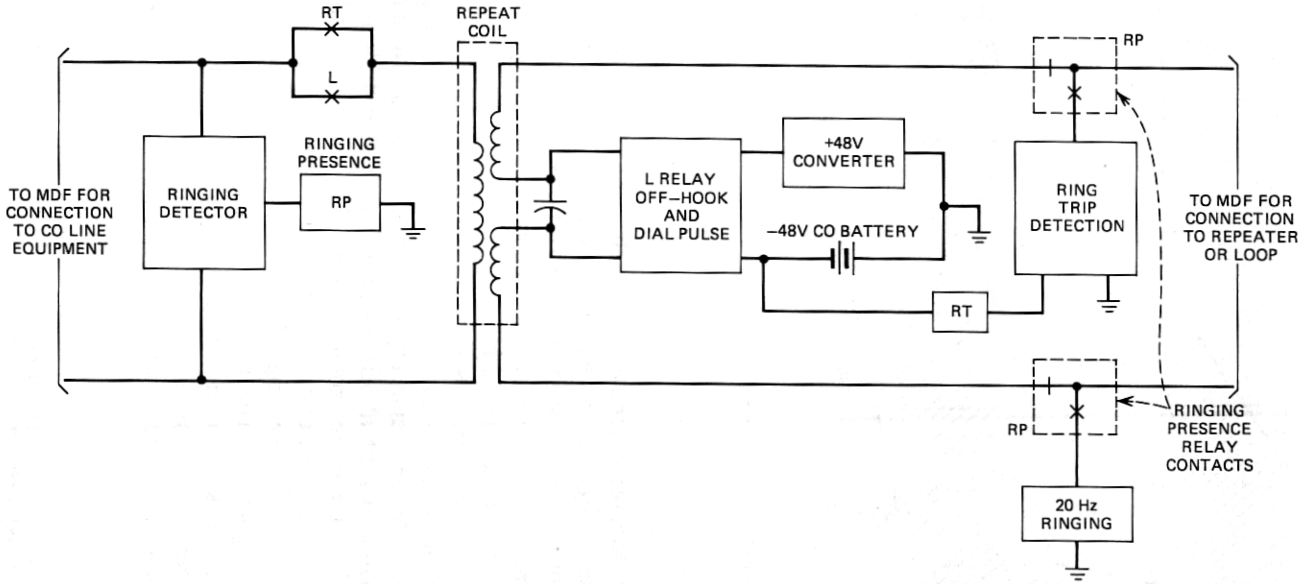

Fig. 2—Typical Dial Long Lines (DLL) configuration (simplified).

1300 ohms without range extension. Newer No. 5 crossbar offices can operate to 1540 ohms and No. 3, No. 2, and new No. 1 ESS offices have a 1600-ohm range, unaided. DLL circuits have been used to extend these ranges to more than 3600 ohms of conductor loop resistance when located in the central office and to 5200 ohms when a second DLL is placed along a cable route.

Twisted cable pairs have much higher voice frequency attenuation than open wire pairs, due to the higher capacitance per unit length. The use of loading coils was adopted by the Bell System early in the 20th century to improve transmission on long cable circuits. Today the H-88 loading plan is used in the Bell System on all loops longer than 18,000 feet. This plan requires 88 mH inductors to be placed at 6000 foot intervals, beginning 3000 feet from the central office.

Loops with resistance greater than 1600 ohms also require amplifiers to aid transmission. The application of solid state circuitry to voice frequency repeater design in the late 1950s for precision equalization of trunk and special business circuits provided an economical subscriber loop repeater as well.[3] The E-6 negative impedance repeaters[4] were the most popular type used in the 1950s and 1960s for loops even though they required more precise adjustments than necessary for residential and single line business service. Figure 3 shows how this repeater can be connected with DLL circuits to provide both range extension and amplification (gain) functions on long loops. The E-6 repeater was particularly convenient to use since its series negative impedance elements were inductively coupled to ring and tip, allowing dc supervision and signaling and 20-Hz ringing currents from the DLL circuit to pass through to the loop.

In the 1950s independent telephone companies and Bell System

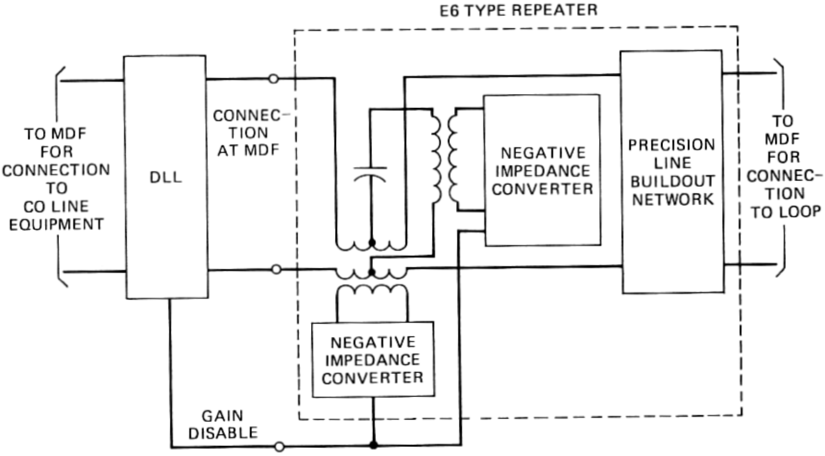

Fig. 3—DLL and E-6 type repeater providing central office range extension and gain.

companies serving rural areas began actively seeking ways in which to reduce the capital expense of replacing open wire and serving new growth in demand with cable. Early loop carrier systems like the M and P1 systems[5] were used as alternatives to cable in some instances, but the greater part of telephone company effort went into the application of voice frequency electronics to effect gauge savings.

A knowledgeable telephone company engineer could select range extension equipment and repeaters for each rural customer service order that was received. The E-6 repeater in such an instance required a relatively complex analysis to determine the positions of approximately 36 screw switches needed to attain precision gain and line-build-out settings. Whenever party line customers were to be added or reassociated, an engineer was required to survey the request to determine when changes in central office circuits and customer loaded cable end-sections were necessary to provide satisfactory service.

While copper savings were obtained in this way, it became apparent that a significant amount of engineering effort was needed to make such a system work. Furthermore, individually tailoring each loop led to a very complex loop network administration. In the 1960s the Rural Electrification Association staff developed a simpler system[6] for the use of electronics by prescription while Bell System companies like Southern Bell were pioneering a similar approach to the use of voice frequency loop electronics. The approach included designing groups (referred to as complements) of loops to serve designated areas (zones) along a rural cable route, prescribing repeater settings for each such group in advance and limiting party line associations to selected pairs available for use only in certain terminals (preferred or restricted pair counts). With this approach, operating personnel in the assignment and installation departments could provide service and reassociate party line customers without engineering participation so long as facilities were available in appropriate customer cable terminals. Prescription design is used in most rural areas of the Bell System today with telephone companies all using a form of the AT&T "Long Route Design" system.[7]

2.2 Suburban areas

In the late 1950s and early 1960s growth of demand in suburban areas served by the Bell System created the need for economy similar to that in rural areas. However, the suburban cable routes were generally shorter (usually less than 50,000 feet) and more densely populated than rural routes. Range extension and amplification applied on a per-line basis in suburban areas are not so economical as for rural areas, since the distances are shorter and the gauges used are 26 and 24 gauge in place of 22 gauge. In rural areas the substitution is typically 22 gauge for 19 gauge or about twice the copper savings per unit length as for suburban routes.

This problem and the growing use of No. 5 crossbar switching equipment with a single line appearance for terminating and originating calls made possible the invention of switched range extension[8] and the Unigauge system.[9]

Switched range extension is the concept of building the extended loop resistance range capability into the switching system and wiring repeaters behind a stage of switching concentration as illustrated in Fig. 4. With such a system the cost of a repeater is divided by the effective* concentration ratio, typically about 3 to 1, allowing economical range extension to be applied to the longer suburban cable routes.

The switched range extension concept was first introduced as part of the Unigauge system in 1966 in No. 5 crossbar. The first application was in Rockford, Illinois. In 1971 this feature was made available in No. 2 ESS[10] and was first used in North Madison, Connecticut. The Unigauge system is intended to maximize the use of 26 gauge cable. The suggested outside plant design is shown in Fig. 5. Note that while other Bell System loop designs call for the use of H88 loaded cable (first load coil 3 kf from the central office with subsequent coils at 6 kf intervals), Unigauge requires only partial loading on loops longer than 24 kf, reducing the number of load coils required.

The Unigauge design has been used to advantage in new wire centers coincident with large-scale additions to the cable plant. However, it has been difficult to use Unigauge in replacement central offices where there are large amounts of existing cable other than 26 gauge. In such cases buffer cable of 26 gauge is required for the Unigauge repeaters to operate with margin against unwanted self-oscillation (singing).

III. RANGE EXTENSION TODAY AND TOMORROW

3.1 Long Route Design

3.1.1 Long Route Design—description and procedures

The Long Route Design system came into use beginning in late 1971 after an extensive study of the rural cable provisioning problem in the Bell System. Concurrently an economical circuit called the Range Extender with Gain (REG) circuit was introduced by Western Electric Company.[11] This circuit, described in detail later, combines the dc signaling and supervisory range extension functions of the DLL with the transmission gain of a negative impedance repeater in a single plug-in unit. The REG circuit is prescribed for use in loops of several resistance ranges or zones as illustrated in Fig. 6. All Long Route Design loops use full H88 loading with 12,000 feet maximum customer end section plus bridged tap.

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* This is the achieved ratio of range extended loops in service to repeaters including spare capacity as opposed to the theoretical ratio (m/k, in Fig. 4).

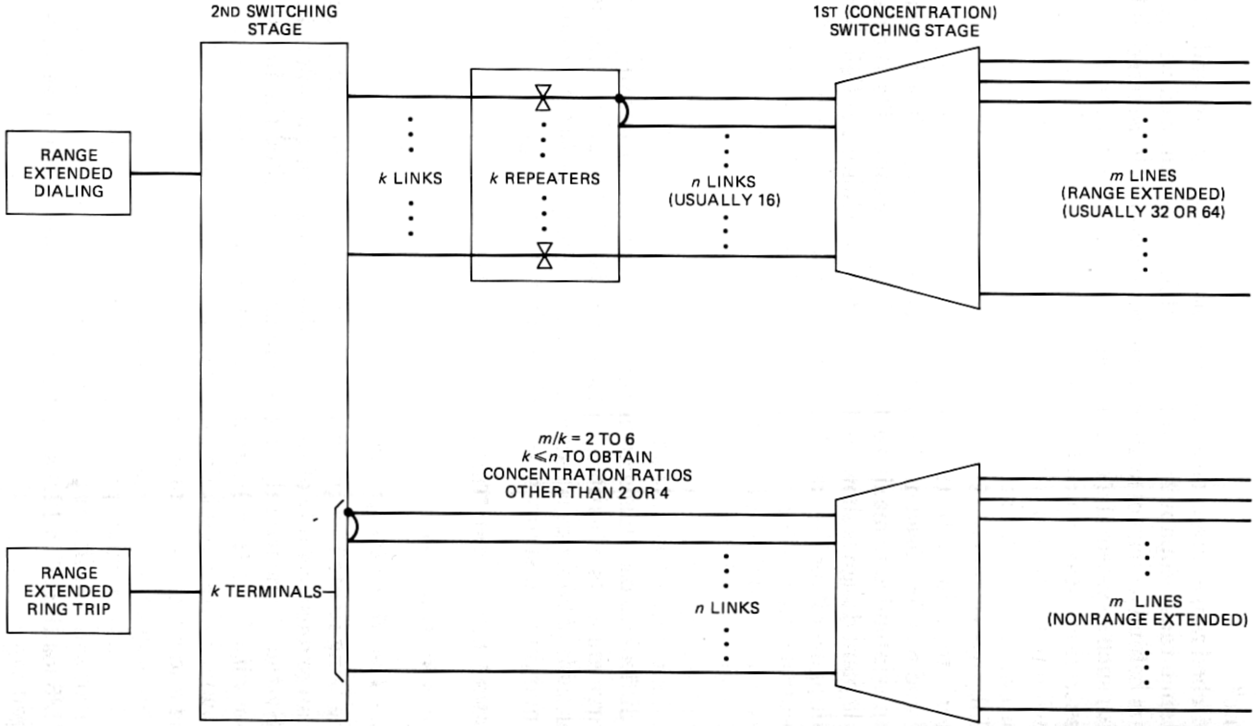


Fig. 4—Generalized switched range extension concept (varies among different switching system designs).

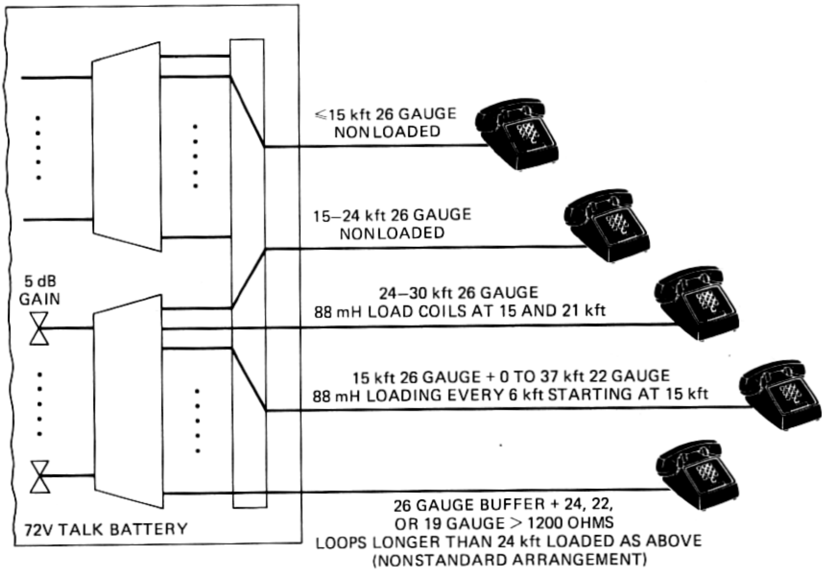
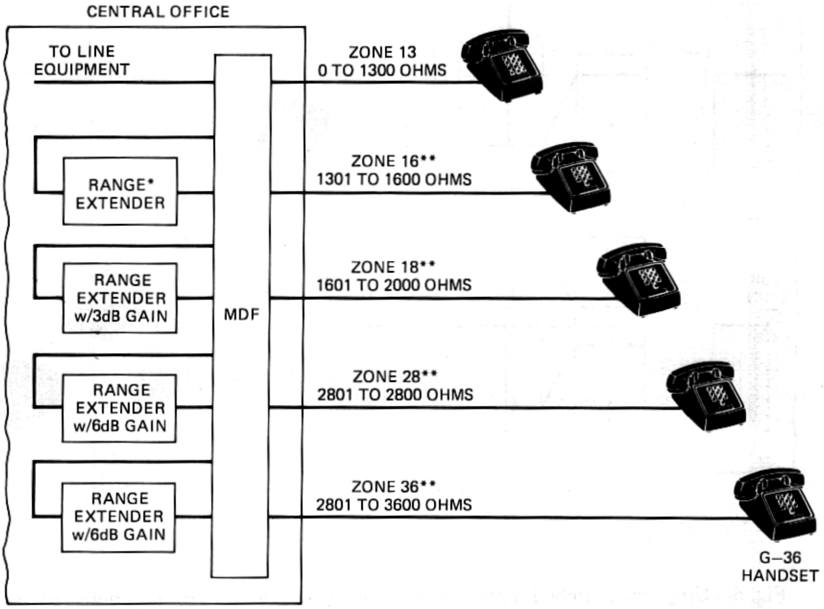


Fig. 5—Unigauge switched range extension system with standard and buffered, nonstandard loops.

Telephone company engineers in applying Long Route Design take into account existing cables, forecast growth in demand, and route length. Several plans may be formulated resulting from different gauging strategies. Typically, some alternative plans will include carrier or concentrator systems as well as voice frequency electronics. The new cable and range extension equipment are evaluated for each plan and a present worth of annual charges (PWAC) comparison of the plans is made. Generally, the plan with the lowest PWAC value over a 20-year study period is selected, subject to local capital constraints. This process results in the selection of gauges for new cable additions which then define the location of resistance zones.

As each cable addition is completed, the plant operations personnel receive the list of available cable pairs in each resistance zone and the record of added central office range extension capacity. When a customer requests service that requires the assignment of a new loop facility, the plant assignment person correlates the customer's premises location with a nearby cable terminal. This is most easily accomplished if the customer has a street address. This is not always possible in rural areas. Sometimes a plant visit is necessary to locate the terminal nearest the customer. The assignment person then searches the cable record for the preferred count in the terminal. If a cable pair is available, it is assigned by notation in the cable record. The cable record also gives the resistance zone number for the terminal from which the pair is assigned. The Resistance Zone Key Record is examined to translate the resistance zone number into



* REQUIRED ONLY IN OLDER ELECTROMECHANICAL OFFICES
**FULL H88 LOADED LOOPS REQUIRED–ANY GAUGE MIX

Fig. 6—Present Long Route Design system.

an equipment type. A Miscellaneous Central Office Equipment Record lists the range extender plug-in slots available for assignment. The assignment clerk transcribes the cable pair identification, zone number and range extension equipment number onto the service order. Central office craftspeople connect the cable pair to the correct range extender and the range extender to the central office line equipment with all connections made at the main distributing frame. In older installations repeater settings were required to adapt the repeater gain to the resistance zone and the repeater line build-out network to the cable pair impedance. As discussed below, with more recent circuits these adjustments are no longer necessary.

In this way all range-extended loops in a route are engineered at one time and, through an orderly administrative procedure, clerical personnel are able to prescribe the electronically augmented facility. This procedure saves engineering time, speeds service to the customer, produces a more orderly loop design over a span of time, but adds some complexity to the assignment and installation functions.

3.1.2 Long Route Design—transmission plan

Before the release of Long Route Design to the operating telephone companies, a very careful analysis was made of the transmission quality as a function of cost. The goal was to provide satisfactory quality while achieving a low-cost system for rural areas. It was determined as a result of this study[12] that a maximum loop insertion loss (at 1 kHz referred to 900 ohms) of 8 dB would guarantee satisfactory service at a reasonable cost for long rural loops. A 10-dB loss design would increase the savings to the telephone company in electronics and cable costs but would cause a disproportionate degradation of transmission quality. A 6-dB design would improve transmission quality but with a substantial increase in system cost. The loss profile of an all 22-gauge cable route using Long Route Design is illustrated in Fig. 7.

While Fig. 7 illustrates a pessimistic 1-kHz loss characteristic along a long cable route using Long Route Design, Fig. 8 shows the loss versus frequency of a 2800-ohm loop with a 6-dB REG repeater compared to that of the highest resistance (1300 ohms) nonrange-extended loop designs. The 2800-ohm loop with repeater is about 1 dB lossier than the 1300-ohm loaded loop at 1 kHz and 2.5 kHz and about 3 dB lossier at 300 Hz. On the other hand the 2800-ohm loop is about 2 dB less lossy than the highest loss nonloaded 1300-ohm loop at 1 kHz and 6 dB better at 2 kHz. This 2800-ohm loop represents a satisfactory design for residential telephone service as indicated by a transmission grade of service study and in fact represents an improvement over the 1300-ohm nonloaded loops that have been standard in the Bell System for the past 20 years.

Transmission grade of service is the expected value of one of two quantities: the percentage of calls "rated" good or excellent or, alternatively, the percentage of calls "rated" poor or unsatisfactory. In either

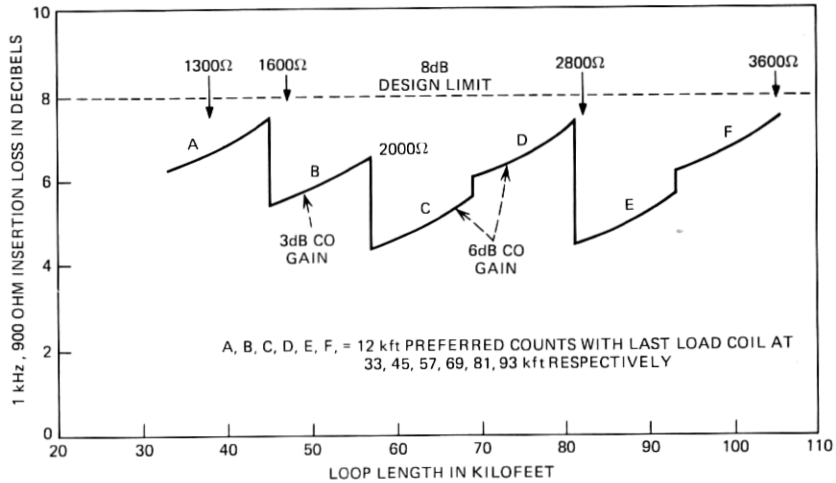


Fig. 7—Long Route Design 1-kHz loss profile—22 gauge route laid out in successive 12 kf (maximum length) preferred counts.

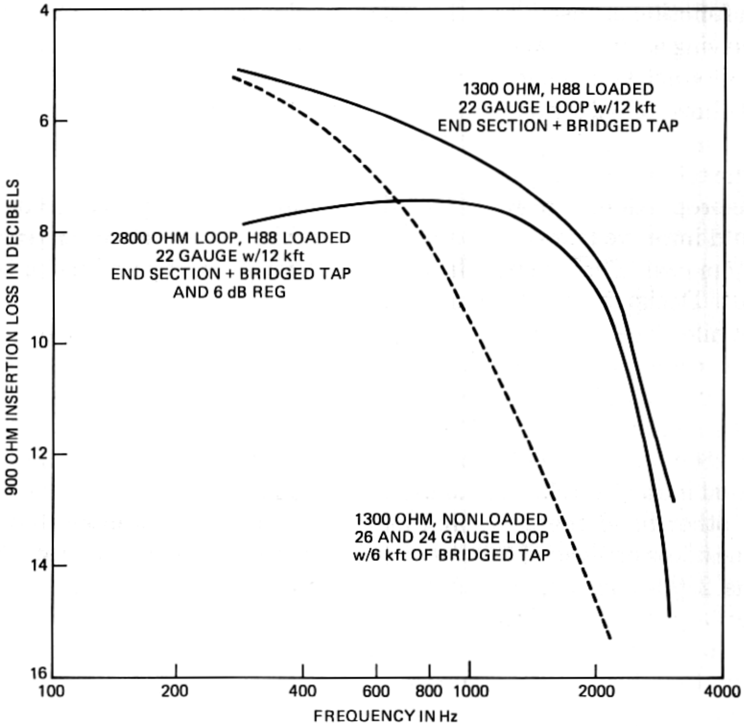
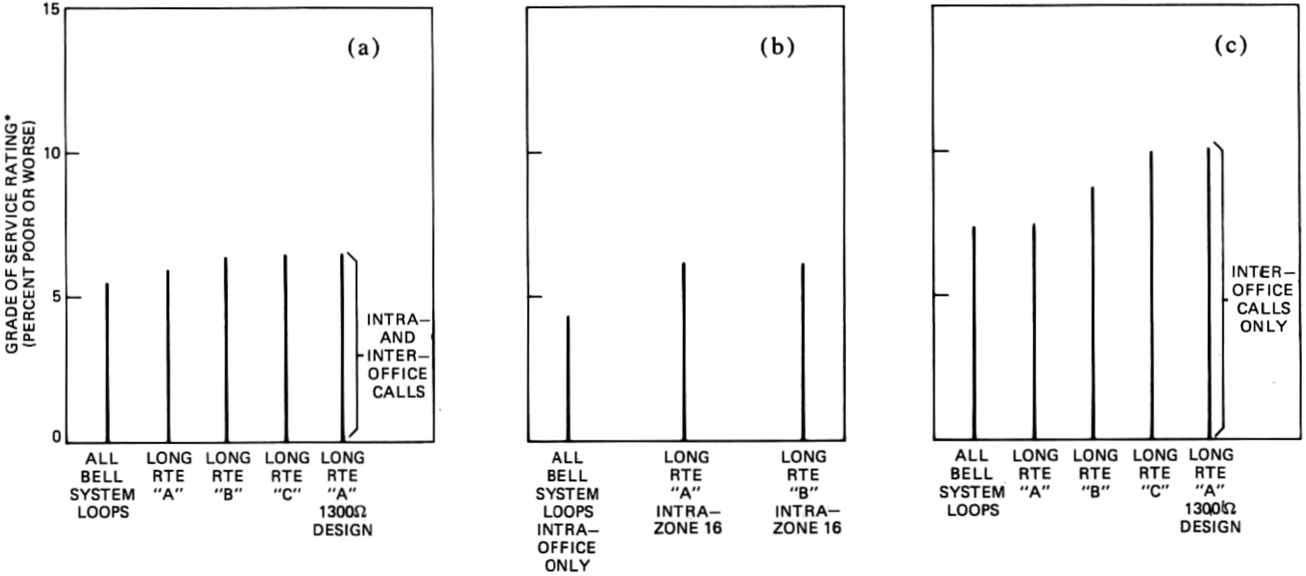


Fig. 8—Loss vs. frequency of maximum resistance range-extended and nonrange-extended loops.

case the rating of telephone connections is based on the results of Bell Laboratories studies whereby people participating in experiments rate the quality of connections on which noise and loss were varied from call to call and does not necessarily represent the absolute ratings that might be achieved in practice. These subjective ratings have been reduced to probability distributions with parameters defined as a function of loop loss and noise.

In the case of Long Route Design, telephone company engineered routes with 20 year forecasts of growth in demand were used as a basis for simulation. Customers were located at random along the route so that each section of the route would have the forecast demand. Each route realization was then used as a data base for a transmission simulation. Each simulation consisted of 1000 connections of five types: community of interest calls (local calls from one Long Route Design customer to another), intraoffice calls and short, medium, and long toll calls to customers drawn at random from a 1973 Bell System loop survey.[13] The expected frequencies of the various types of call were set at approximately 0.20, 0.46, 0.29, 0.04, 0.01, respectively.

The results in Fig. 9a show the overall grade of service performance



* Grade of service in this context is not a prediction of absolute performance but is intended to be a reliable indicator of the *relative* performance of two or more comparative systems.

Fig. 9—(a) Overall Long Route Design grade of service. (b) community of interest calls. (c) toll call performance.

for several study routes comparing Long Route Design results to those of a random sample of 1100 Bell System loops. In Fig. 9b the community of interest call performance for zone 16 is shown for two routes and compared to overall Bell System intraoffice grade of service. In Fig. 9c the performance on toll calls is shown for long routes and compared to the Bell System norm. Also shown in Fig. 9c is the toll call performance for one of the long routes designed, using 19 gauge cable, to a maximum resistance of 1300 ohms requiring no range extension, this being the voice frequency alternative to Long Route Design.

It is seen from these results that overall transmission performance of Long Route Design loops is comparable to the general Bell System performance but that toll call performance is somewhat degraded. This is due to the fact that general Bell System loops have losses ranging from 0 to 10 dB with an average of 4 dB. Long Route Design loops range from about 4-dB to 8-dB loss with an average of 6 dB. The trunking loss in toll connections tends to reduce echo effects and at an average of 6 to 7 dB is enough to affect the quality of calls involving Long Route Design loops. However, in Fig. 9c it is apparent that long route A experiences about the same toll transmission performance, whether designed to 1300 ohms, using costly 19 gauge cable, or designed to 2800 ohms with half the copper, using 22 gauge cable and voice frequency electronics. This example illustrates that when loops are sufficiently long to place them at the high end of the Bell System loaded loop loss distribution under the 1300-ohm standard maximum loop resistance design, service will be as good or better with the more economical 2800-ohm design.

These results have led to the conclusion that the 8-dB maximum loss design with 6-dB average loss is satisfactory for all long route applications.

3.1.3 Long Route Design—other transmission factors

In addition to the loss plan, the Long Route Design loops must satisfy other transmission objectives: crosstalk, noise, delay distortion, and return loss.

The Bell System objective for noise at the terminals of the customer's service drop is 20 dBrnc. It is generally recognized that noise performance on loops is dominated by induced harmonics of 60-Hz power transmission and by the electrical balance of the telephone physical wire pair and its terminations. The induction of 60 Hz and harmonics as a common mode signal into paired telephone cable is enhanced by increasing the length of the exposure to power line coupling. Long rural cable routes, therefore, have a greater likelihood of experiencing voltage above any threshold value than shorter urban routes. The Long Route Design transmission plan assumes a level of 25 dBrnc present at the subscriber terminals for this reason. Grade of service studies assumed this noise level on Long Route Design loops. Loop noise is also a function of terminal balance at both ends of the loop. Figure 10 gives the requirement for range extension circuit balance and shows the test circuit used to verify performance. Experience has shown that longitudinal noise on long loops can exceed 50 V rms. The balance requirement is necessary to attain less than 25 dBrnc of unwanted metallic circuit noise. The telephone set floats with respect to ground at the station end of the loop on individual line service with bridged ringers and is not a significant factor in common mode conversion. However, many (several million) rural loops continue to serve party lines and require grounded ringer operation. In the same category are the affluent long route customers with 4 or 5 ringing telephones, whose telephones must be rung through a connection to ground to increase the power delivered to the ringers on high resistance loops.[14] Connecting the ringers to ground at the station creates an electrical unbalance and increases unwanted longitudinal-to-metallic conversion. The solution to this problem has been to use ringer isolation circuits that provide a low impedance path from ringer to ground when ringing is present but isolate the ringer from ground when ringing is not present, maintaining station balance during the conversation.

A second degradation is crosstalk. Long Route Design loops have increased susceptibility to the near-end crosstalk phenomenon, illustrated in Fig. 11. Consider the case where two active Long Route Design loops are connected to two short loops. The signal level arriving at the central office from the short loop station is relatively high and is amplified by the range extension repeater. Crosstalk occurs within the cable, dominated by coupling between pairs near the central office, and experiences low propagation loss back to the CO on the other long route cable pair. The crosstalk is amplified again in the opposite direction by another repeater and experiences low loss to the disturbed customer station. For every added decibel of repeater gain, near-end crosstalk levels are increased by two decibels. The currently accepted objective for crosstalk allowed is 0.1 percent chance of hearing intelligible crosstalk in any given conversation. A repeater with more than 6 dB of gain at 1 kHz exceeds that 0.1 percent objective in today's loop plant.[15] This fact along with the 8-dB maximum loop loss establishes 2800 ohms as the highest-resistance H88 loaded loop that can be served with central office gain alone. It is possible to extend loops to 3600 ohms with 3.5 dB of transmit and receive gain at the station, as is done with the G-36 handset, without violating the more stringent crosstalk design limit at the station end of the loop.

Talker echo is a very annoying transmission degradation on long toll calls. This echo is dependent on obtaining matched impedances at trunk terminations. The impedance of a loop terminated in an off-hook tele-

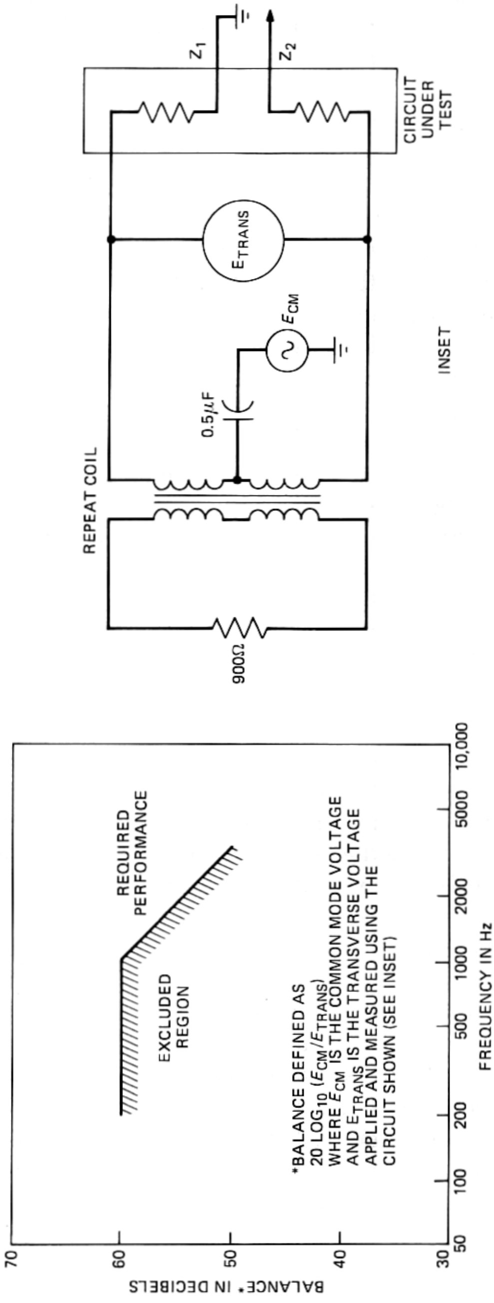


Fig. 10—Range extension circuit terminal common mode balance requirement.

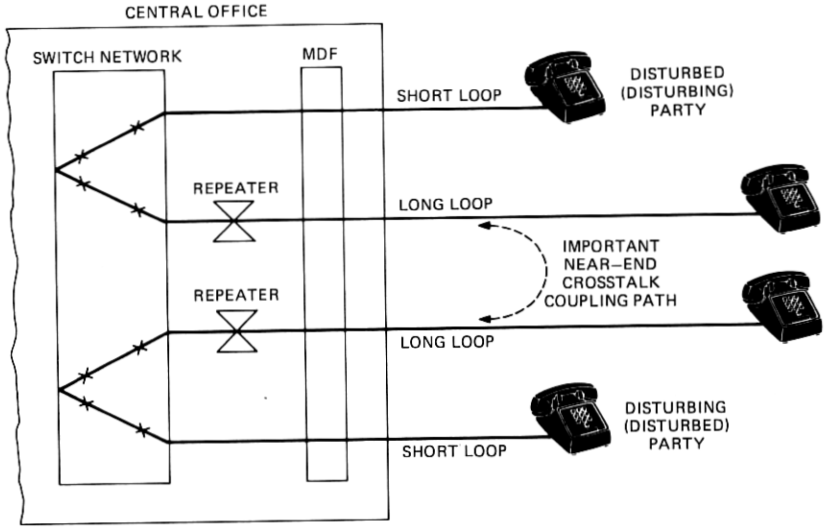


Fig. 11—Range extension repeater near-end crosstalk problem.

phone set is quite variable due to the large range of loop lengths and the intermixing of four wire gauges. This impedance is related to echo by the equation for return loss:

$$\text{return loss} = 20 \log_{10} \left| \frac{Z_{\text{Loop}} + Z_o}{Z_{\text{Loop}} - Z_o} \right|$$

where Z_{Loop} is the impedance of the loop measured at the central office with an off-hook telephone set and Z_0 is the reference impedance. In this case Z_o has traditionally been taken to be 900 ohms in series with 2.16 microfarads. Echo return loss is defined as a weighted average of return loss between the frequencies of 500 and 2500 Hz. Bell System loops have evolved with an average echo return loss of 11 dB with a standard deviation of 3 dB. Repeaters that are part of range extension circuits should and typically do exhibit better than average performance in this respect.

A degradation related to echo is the near-singing or "rain barrel" effect that is sometimes experienced. This is controlled by placing an objective on singing return loss, the lowest single frequency value of return loss in the range of 250 to 3200 Hz. This objective is related to an existing Bell System average value for loops of 6 dB, standard deviation of 2 dB referred to 900 ohms in series with 2.16 microfarads. The objective for voice frequency loop repeaters is that their use makes long loop performance no worse than Bell System overall performance.

A method of controlling return loss other than by impedance matching is voice-switched gain, used in echo suppressor circuits. These circuits control echo by sensing the direction of transmission in the four-wire path on long toll connections and then introducing high loss in the opposite direction. This technique is also used in *SPEAKERPHONE*® design to reduce acoustic feedback. It is possible to use voice-switched gain in loop repeaters. Voice-switched gain circuits must by necessity respond to the initial spoken syllables. The switching action occurs at this time and may impair transmission. Examples of possible impairments are loss due to false switching, increased break-in difficulty, and speech clipping. It is a current Bell System recommendation that voice frequency repeaters for loop range extension not use voice-switched gain to control return loss.

Data transmission has increased in the loop plant and requires control of phase distortion as well as loss. This equalization is currently custom-engineered by the telephone companies and not provided by range extension circuits. As the incidence of data transmission in the long loop areas grows, there may be an impetus to provide prescription equalization for range extended loops.

Voice frequency repeaters must not distort signals of reasonable amplitude. The recommended distortion requirement is less than 0.5-dB compression of any single frequency in the range of 300 to 3300 Hz at a peak level of +6 dBm into 900 ohms. As an objective, repeaters should be linear in the 300 to 3300 Hz range up to signal levels of +10 dBm.

3.2 Future direction

Further evolution of Bell System outside plant voice frequency loop design is possible. As seen in Fig. 8 nonloaded 1300-ohm loops have higher loss over much of the voice band than 2800-ohm rural loops with 6-dB repeater gain. It is also the case that with the introduction of No. 1, No. 2, and No. 3 ESS offices in the past 13 years, central office supervisory range is not necessarily limited to 1300 ohms. The No. 2 and No. 3 ESS systems have circuit options built in for 1600 ohms of conductor loop resistance and the No. 1 ESS has recently added such a feature. Appropriately equipped existing No. 1 ESS and No. 5 crossbar systems can operate to 1500 ohms of conductor loop resistance. New cable, placed in the past decade, has largely been buried or in underground ducts, reducing the resistance margin necessary to allow for aerial cable in hot weather. These facts suggest a new standard design for nonrange-extended loops of 1500 ohms resistance instead of 1300 ohms. Such an increase would provide gauge savings and, if REG circuits are used on loops over 1500 ohms, the elimination of resistance Zone 16 as an administrative entity in all but older step-by-step switching systems. To improve transmission, loading can be used on loops longer than 15,000 ft instead of 18,000 ft from the central office. This will eliminate the longest nonloaded loops and their high loss, while not affecting average loop loss. Such a plan would also remove the lossiest Zone 16 loops.

To help make this plan a reality, a concentrated range extender is being designed for use in No. 1 and No. 2 ESS offices to be compatible with fully loaded loops of any gauge mix so that urban (1500-ohm maximum loops), suburban (2800-ohm maximum loops, concentrated range extension), and rural (2800-ohm maximum loops, per line REG) switching centers can have a unified loop design with maximum range extension economy consistent with good transmission and high reliability and relatively simple administration.

IV. RANGE EXTENSION FUNCTIONS

As just discussed, unaided loop telephone service becomes marginal when loop cable resistance exceeds about 1300 ohms. To some extent this threshold is a function of switching system type. Beyond 1300 ohms, deficiencies occur in both signaling and transmission. More specifically, the functions needing enhancement for long loops are origination, dial pulsing, ring trip, telephone set transmitter current, voice frequency transmission, and ringing.

ORIGINATION. Office line circuits require a minimum of 10 to 16 mA to detect a call origination. Loops of 2800 ohms resistance, the maximum standard range-extended loop, draw a minimum of about 10 mA. Some older small step-by-step offices with high-resistance line circuits provide only 7 mA. Therefore all step-by-step and most crossbar offices require assistance in detecting call origination on loops between 1300 and 2800 ohms.

DIAL PULSING. Office circuit resistances are lower during dial pulsing than during origination; however, office circuit thresholds are higher and the relation between loop currents and the threshold is more critical to preserve dial pulse fidelity. Consequently, long loops for all offices require dial pulsing assistance.

RING TRIP. Loop currents when a called party answers during ringing are greater than those during origination; however, office circuit thresholds are also higher and again all offices require assistance when serving long loops.

TELEPHONE SET CURRENT. The telephone set is designed to perform acceptably over a 20- to 80-mA range of loop currents. Below 20 mA *TOUCH-TONE®* dials become marginal at low temperatures and the set transmit gain function suffers. All range extenders provide a form of boosted battery to maintain a minimum of 20-mA loop current.

VOICE FREQUENCY TRANSMISSION. Long loops in the Bell System are always loaded (H88 type). For these loops the loss is proportional to resistance (Fig. 12) and at 1600 ohms approaches 8.0 dB worst case, the maximum loss limit for Long Route Design loops. Beyond 1600 ohms supplementary bilateral gain is required.

RINGING. Ringing does not normally require enhancement to operate

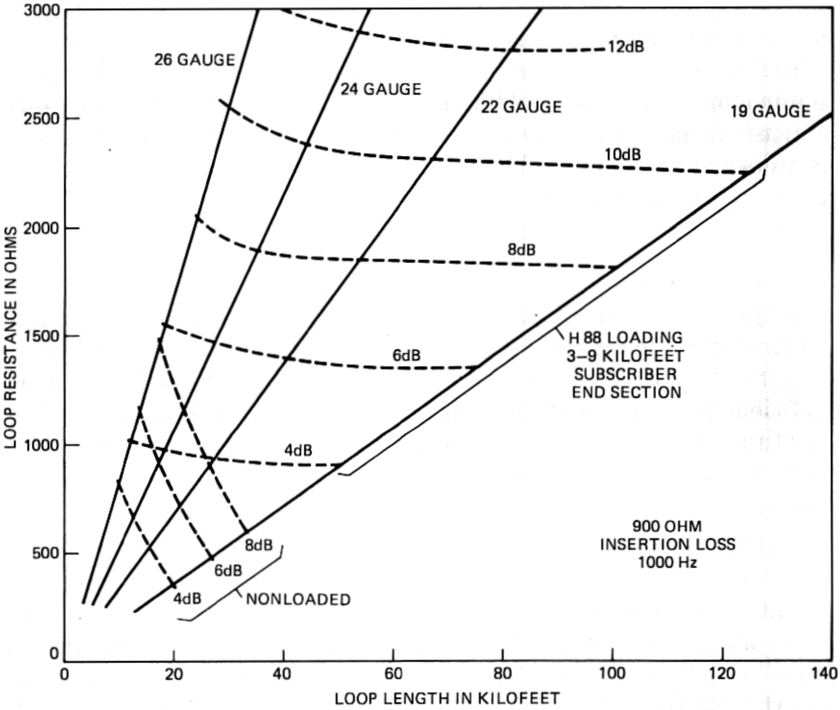


Fig. 12—Loop cable resistance and loss vs. loop length. Present Long Route Design requires H88 loading beyond 18,000 feet and range extension beyond 1300 ohms.

three bridged ringers at 2800 ohms. Ringing range can be a significant problem when more than three ringers are required. A ringer isolation device is normally required for party line service where ringers must be rung to ground but otherwise isolated to prevent loop imbalance and enhanced sensitivity to 60-Hz longitudinal induced currents. Ringing aid devices are, therefore, common on long routes and will be discussed as part of this article.

V. THE RANGE EXTENSION ENVIRONMENT

Before discussing range extension circuits in the next section, it will be helpful to discuss briefly the range extension environment including cable and office characteristics.

Long route cables differ from those within the normal office limits in that they have higher resistance and loss. The prime purpose of range extension devices is to compensate for this increased resistance and loss, to bring them within acceptable limits. Other long route cable characteristics are impedance and cable irregularities. These characteristics do not differ significantly from loaded short cables; however, they do influence range extension circuit design considerably.

The range extenders under discussion here are located in the central office and are terminated on one port by the office switch. This interface is a complex one when considering the variety of switching machines, switching circuits, and operating modes. A general-purpose range extender should be as broadly compatible as possible. A few of the dominant office features influencing range extender design are also presented here.

5.1 Cable impedance and stability considerations

The voice frequency impedance of the cable pair is important because it has a strong bearing on amplifier stability and also because it influences power transfer into the cable. Range extension amplifiers (commonly known as repeaters) are bilateral gain devices and consequently their gain and stability depends on the terminating impedances at both ports, i.e., that of the loop pair and the office termination.[16] As the office impedance is constrained only to being positive real in a practical sense, then it falls on the loop impedance to determine the maximum practical amplifier gain. If this impedance is too variable then the amplifier configuration must be customized around each of several cable impedance subsets. Even if this customization is achieved by screw adjustments on a prescription basis, there is a significant administrative penalty. For POTS service, freedom from all field adjustments is an important goal.

Figure 13 shows typical impedances for Bell System loops over 1300 ohms. The impedances are shown on a Smith chart impedance grid normalized to 900 ohms. When scaled in this manner, distances between impedances tend to correlate, with the difficulty in matching a repeater to these impedances in a stable, non-oscillatory manner. It is obvious that loaded loops form a much more constrained set of impedances than nonloaded loops. This fact, in addition to the "gain" provided by the load coils, makes loaded loops definitely preferable for long routes. With a nonadjustable amplifier, 6 dB of bilateral repeater gain is practical for Bell System H88 loaded loops. With nonloaded loops only about 5 dB at 1-kHz fixed gain is practical and then only if the impedance spread is constrained by a 3000- to 5500-foot section of 26 gauge buffer cable at the office end of the loop. This latter design is the basis of the Unigauge loop network used in a few Bell System wire centers.

The H88 loaded impedances of Fig. 13 are for "good" loops. Good loops are ones with 3000-foot office end sections and are either long loops or, if short, have 3000-foot subscriber end sections. Range extenders must also work on minimum length loops with 12,000-foot subscriber end sections, and on loops with some load coil placement deviations. Figure 14 shows the impedance of a pair of worst case allowable Long Route Design loops giving a hint of the variations possible.

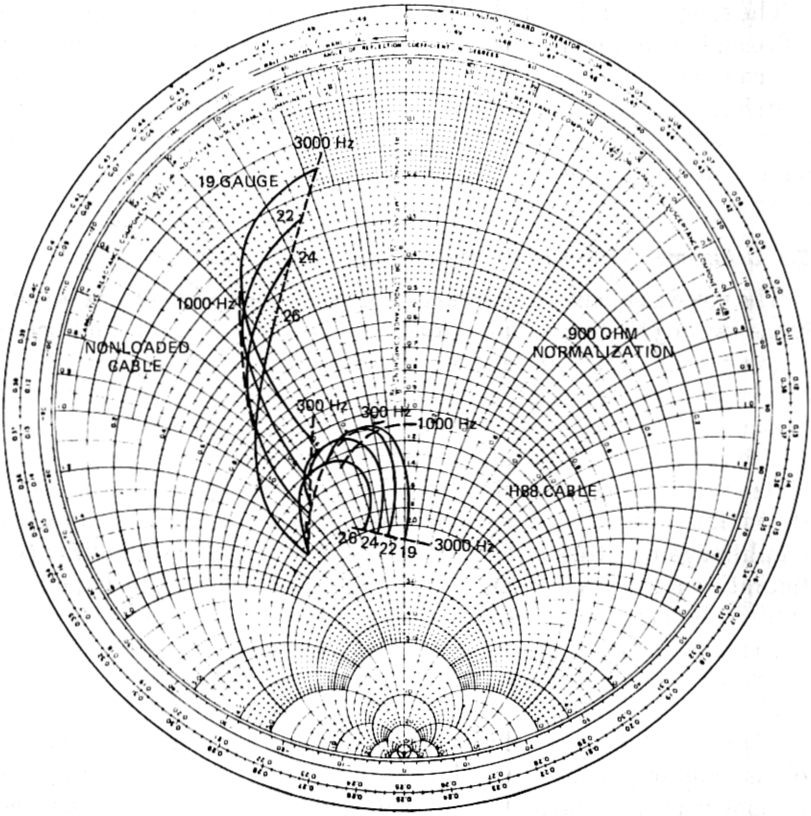


Fig. 13—Loop cable impedance vs. frequency for electrically long H88 and nonloaded loops.

An attempt has been made to define all allowable Long Route Design loops and to determine their impedances at critical frequencies. Figure 15 shows this impedance spread for the midband 1000-Hz frequency and the band edge frequencies of 300 Hz and 3000 Hz. Proper matching network design can transform these sets of impedances to a nominal 900 ohms. Their spread is sufficiently small to allow 6 dB amplifier gain, an unconstrained positive real office impedance, and still have unconditional amplifier stability.

H88 loading is specified by 88-mH load coils, spaced 6000 ± 120 feet apart, starting 3000 feet from the office. The subscriber end section plus bridged tap limits are 3000 to 12,000 feet and neither loaded bridged tap nor bridged tap between loads is allowed in Long Route Design. Unfortunately plant deviations are common and a reasonable tolerance to these is desired. One approach is to group network irregularities into two categories, minor and major.

A minor irregularity is an error in load coil location of 500 feet or a

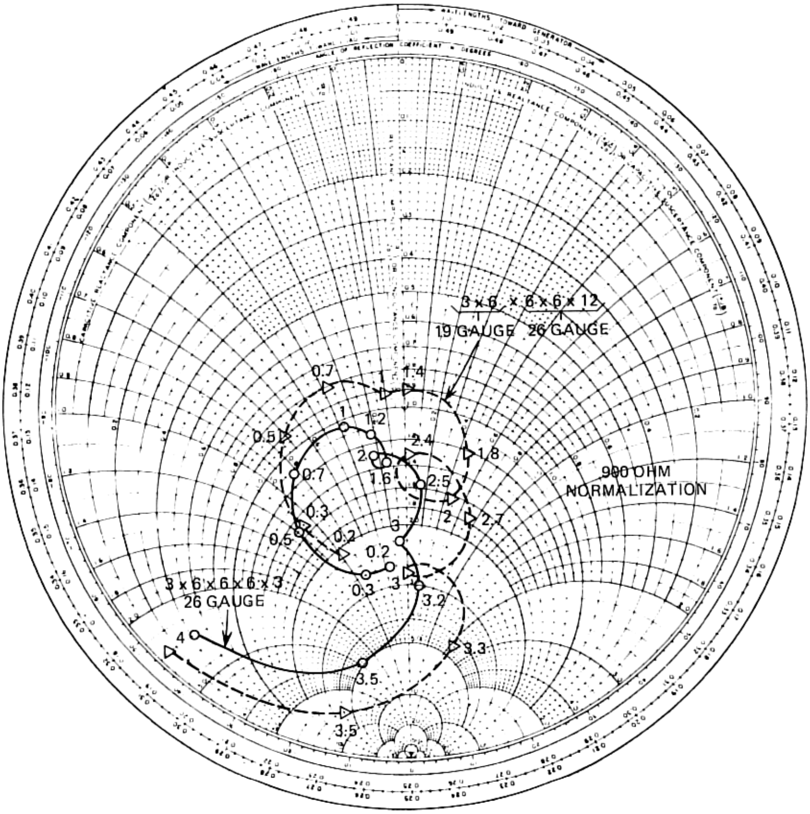


Fig. 14—Impedance vs. frequency for two worst-case Long Route Design loops.

500-foot bridge tap, within the first five load sections. Beyond about five sections errors can be several times greater. The effect of these on loss is limited to a few decibels at most, and as an objective any associated repeater should be stable.

Major irregularities include missing or doubled load coils, spacing errors of greater than 500 feet in the first five load sections, and loaded bridged tap. In this category transmission loss can be affected by many decibels and even if such a loop is stable it may be service-affecting and should get priority maintenance attention. Repeater stability on such loops is not expected and is not a design objective. Rarely do offices have more than a few percent of loops in this category.

5.2 Office response times

A finite delay exists between an off-hook telephone set signaling call

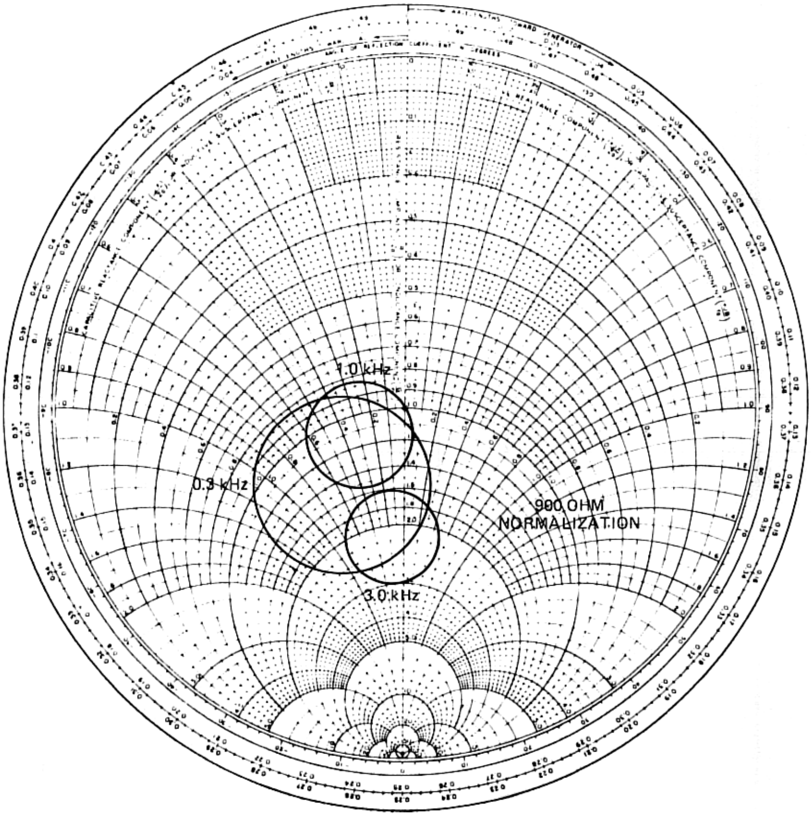


Fig. 15—Impedance boundaries at band center and band edges for all allowed Long Route Design H88 loops.

origination and office switch response. These delays range from about 50 msec to several hundred milliseconds or longer during high traffic delays. The switching network is reconfigured, in general, several times in establishing a talking path. Loop current is broken during these operations, affecting range extender loop current sensing. After network reconnection, different delays occur before subsequent switching circuit response. Throughout these sequences the range extender must work compatibly. A sufficient design is one that responds faster on resumption of loop current than the associated switching circuit. In this mode the range extender appears transparent to the switch and compatibility is assured. Range extender design is frequently simplified if slow response times are implemented, but the interface with the switch then has a new dimension, that of time, and the interface is appreciably complicated.

5.3 Switching circuit source impedance

In general, standardization of source impedance exists among office types for a given operating mode. In existing offices, for example, talking circuits are invariably 400-ohms dc resistance, ringing circuits are under 400 ohms, 20-Hz impedance, and dial pulsing circuits are about 400 ohms resistance. Line circuits that detect call origination, however, have greater variation, ranging from 500 ohms to 1300 ohms typically but reaching 3200 ohms for a particular widespread step-by-step circuit. This latter circuit is especially annoying in the design of range extenders. Switching systems under development but not yet in service are tending toward high impedance, constant current battery feed. These circuits are generally compatible with existing range extender designs.

5.4 Tip party identification circuits

In the Bell System the calling customer for two-party service can be automatically identified. When off-hook the tip party customer's set connects a 2650-ohm resistance to earth ground. The office senses this path by breaking loop current and attempting to force a current from tip to ground. Repeat coil type range extenders, to be discussed later, break this current path and are, therefore, basically incompatible.

5.5 Office talking circuit balance

As discussed earlier a loop cable pair is balanced with respect to ground. Office and telephone set circuits are also balanced, thereby offering high immunity to longitudinal currents induced by nearby power lines. Office talking circuit balance ranges from a minimum of 40 dB for some step-by-step offices to over 60 dB for ESS offices. As long loops tend to have greater induced currents, it is imperative that range extenders for step-by-step and crossbar offices provide an improved balance to the loop to effect the requirements of Fig. 10.

5.6 Ringing waveform crest factor

Essentially all loop ringing in the Bell System is 20 Hz superimposed on a dc trip bias battery. As discussed earlier, ringing aids are frequently used on long routes. These circuits must detect the presence of ringing voltage. As most of these circuits are peak voltage sensors the ringing waveform crest factor can significantly affect ringing aid operation. Crest factors range from 1.2 to over 1.6 as a function of ringing plant design. This factor is a significant variable affecting ringing aid operation. An example is the cold-cathode gas tube used for selective ringing detection where low crest factors can cause marginal triggering.

5.7 Testing circuit compatibility

Bell System offices have a variety of circuits for testing for loop faults. The first requirement for testing is to provide loop access. Range extenders should have a reliable dc path through the circuit; otherwise office personnel must manually connect a test shoe to gain loop access. The lack of a "test-through" capability can be a liability, particularly when the office is equipped for routine automatic loop testing.

A second requirement imposed by test needs is to minimize leakage currents created by range extender circuits. These conductive paths mask cable faults in that the office test circuits cannot distinguish differences. Requirements on range extenders to assure compatibility are for tip-to-ring and tip- or ring-to-ground resistances to have minimum values on the 1- to 3-megohm range; higher values are desirable.

VI. RANGE EXTENSION CIRCUITS

Attention can now be focused on loop range extension circuits that have evolved in the last few years.

6.1 Dial long line circuits and E6 repeaters

In the late sixties long loops were treated using dial long line circuits (DLLs) and E6 repeaters (Fig. 16). The DLLs by then had evolved into plug-in assemblies for compactness and ease of maintenance. The DLLs were sometimes used alone where telephone companies allowed loop designs with more than 8-dB loss. These DLLs were generally characterized by:

Individual shelf mounting, 12 circuit capacity
72- or 96-V boosted loop battery
97-Vac repeated loop ringing
Repeat coil with good balance
Repeated selective ringing
Repeated dial pulsing
Repeated ringing trip
No test-through arrangement
No tip party identification circuitry
A family of units for different ringing services
Ballast lamps for short circuit protection

Some of these characteristics are shown in Fig. 2. Boosted loop ringing was employed to provide some ringing range extension especially when driving gas-tube-isolated ringers. Boosted loop battery provided 20-mA current over 3600-ohm loops in addition to the E6 repeater resistance. In the last few years the DLL approach has lost favor primarily because of no test-through capability, no tip party identification, and the size, cost, and multiplicity of units required for party-line ringing options.

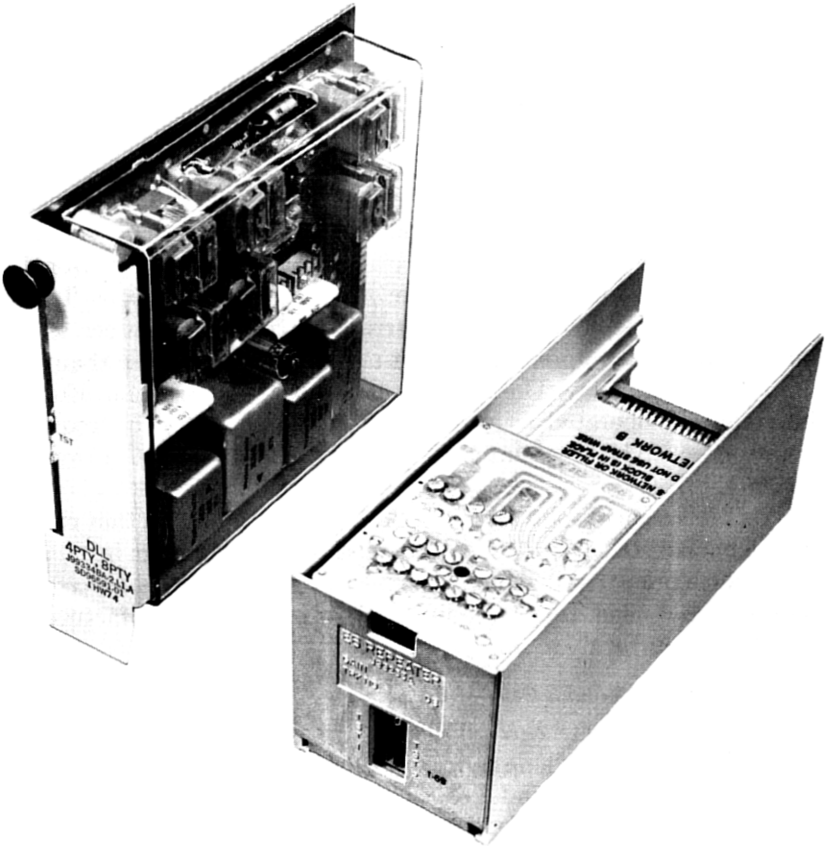


Fig. 16—Dial long line (left) and E6 repeater (right) plug-in units.

Voice frequency gain was provided by the E6 repeater, a two-wire negative impedance amplifier as previously mentioned.[4] It could be connected in tandem with the DLL circuit, preserving dc continuity for loop powering and signaling while adding up to 13-dB gain (Fig. 3). Optional adjustable matching networks were available for either port to match resistance, nonloaded cable, or loaded cable terminations. Other characteristics were:

Separate shelf mounting, six across
Negative impedance repeater with shunt and series elements
Broad matching capability with many screw adjustments
Gain to 13 dB in 0.1-dB steps through many screw adjustments

The E6 repeater was designed for exchange trunk and special services applications where its performance and circuit flexibility were required. For loop service the cost of its separate mounting and complexity of adjustments were liabilities.

6.2 2A range extender

One of the first devices to provide signaling range extension in a more attractive form was the 2A range extender.[17] Step-by-step and crossbar offices both employ relays for supervision and line monitoring in the on-hook state. The single most limiting aspect of these offices in serving long loops is the current required to pull in these relays upon call origination. Maximum ranges of 1300-ohms loop resistance are typical. However, once the line relay is operated the current drawn by loops over 1800 ohms is sufficient to hold the relay operated. This results from the well-known hysteresis characteristic of standard relay designs. The 2A range extender exploits this characteristic by placing a shunt across, say, an 1800-ohm loop upon origination to make it appear less than 1300 ohms to the line relay. The 2A shunt is removed in 0.5 second, after the line relay has operated, so as not to affect subsequent voice frequency transmission. The 2A shunt is operated by a sensitive loop current detector.

The 2A is a small solid state circuit, as shown in Fig. 17, that mounts on the main distributing frame. With attributes of minimum installation effort and a price that is about one-sixth of a DLL, the 2A has successfully met a special need. Introduced in 1967, it is still in manufacture and 500,000 are currently in service.

6.3 Range Extender with Gain—REG

About 1970 it was recognized that significant improvements could and should be made in the loop range extender art. Loop loss control was of increasing importance and a maximum 1000-Hz loss of 8.0 dB was an accepted design limit. This limit meant that gain was necessary for all loops over 1600 ohms. With long range extended loops becoming more common (a few offices had over a thousand DLLs and E6s), size and cost were important. The need for a test-through capability was also evident.

To fill these needs a combination Range Extender with Gain (REG) was devised by J. L. Henry and L. G. Schimpf of Bell Laboratories.[18] This REG List 1 was a single solid state plug-in assembly, Fig. 18, that mounted 93 to a 7-foot bay. The bay also contained a common bay power supply for the boosted battery. The installed cost was about half that of the DLL-E6 combination it replaced. Major characteristics were:

One unit served all single and multiparty service
Compatible with office tip party identification
Idle state bypass allowing test-through
No adjustable relays requiring maintenance
1600- to 2800-ohm range
Gain of 4 or 6 dB set by screw adjustments
Cable matching network with five screw adjustments

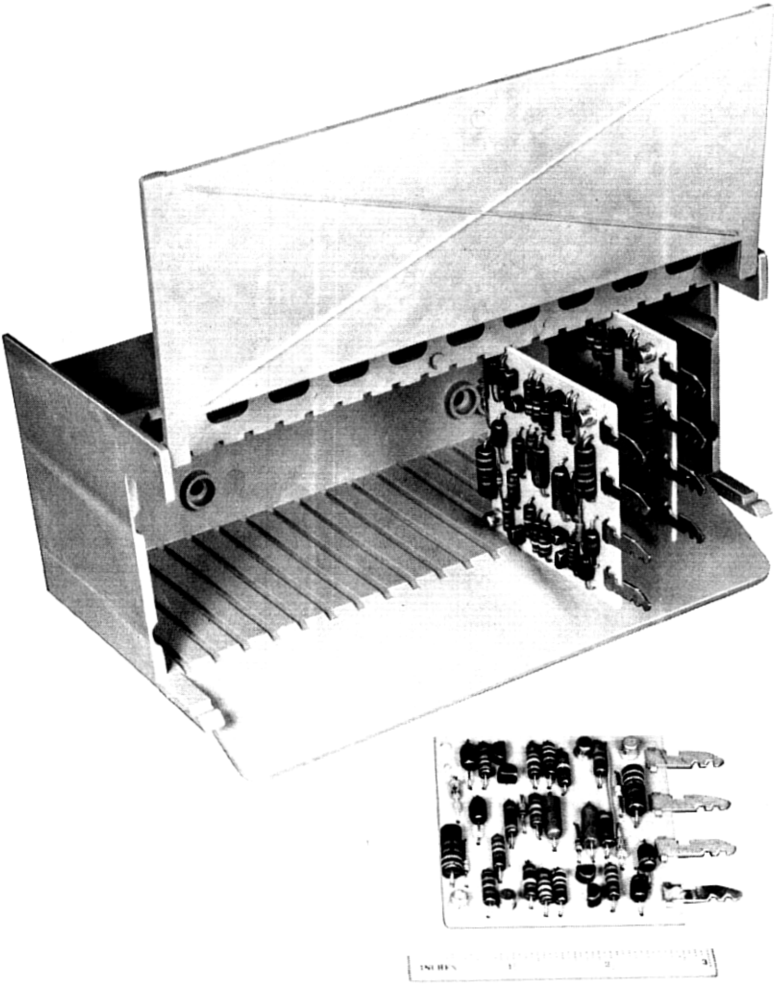


Fig. 17—2A range extender and distributing frame apparatus mount.

All adjustments set by prescription based on resistance zones and cable characteristics
Solid state devices providing short circuit protection
Repeat coil for good balance
Fast-responding range extension circuit
Negative impedance amplifier

This first REG List 1 offered in 1971 was a success and was followed in 1973 by a reduced-cost version known as REG List 2. Cost was reduced by simplification of the signaling and logic circuitry, allowing elimination of one printed circuit board. One consequence of simplification was that the circuit now operated more slowly than some office switching machine

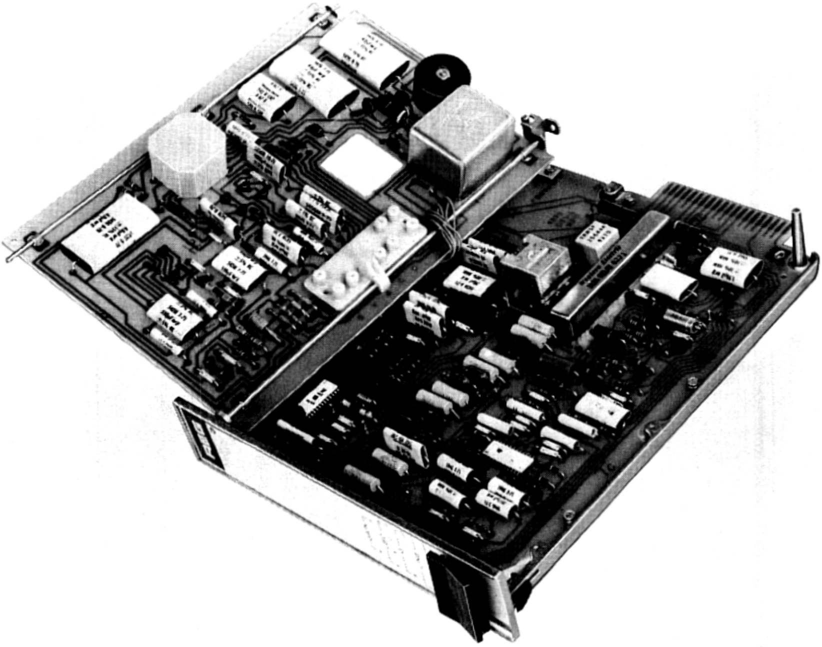


Fig. 18—Range Extender with Gain (REG) List 1 showing swing-out daughter board.

functions. A program patch was required in No. 1 ESS to achieve compatibility.

In 1975 the REG List 3 was offered. It was part of a Zone 36 package and differed from REG List 2 only in that it had an additional screw adjustment allowing a lower loop current threshold for the more distant zone.

6.4 5A REG

In 1976 the REG family was further improved with the introduction of the 5A REG. While retaining the same plug-in format of previous REGs it offered a 24 percent cost reduction and the following features:

3 or 6 dB gain automatically controlled by loop resistance
Single line matching network for all H88 loaded cable
Elimination of all adjustments
Operation on loops as short as 1000 ohms
Improved reliability
Improved stability

The 5A unit is shown in Fig. 19. The 5A REG has been well received by the operating companies, not only because of the cost reduction but also because the elimination of all adjustments allows simple administration.

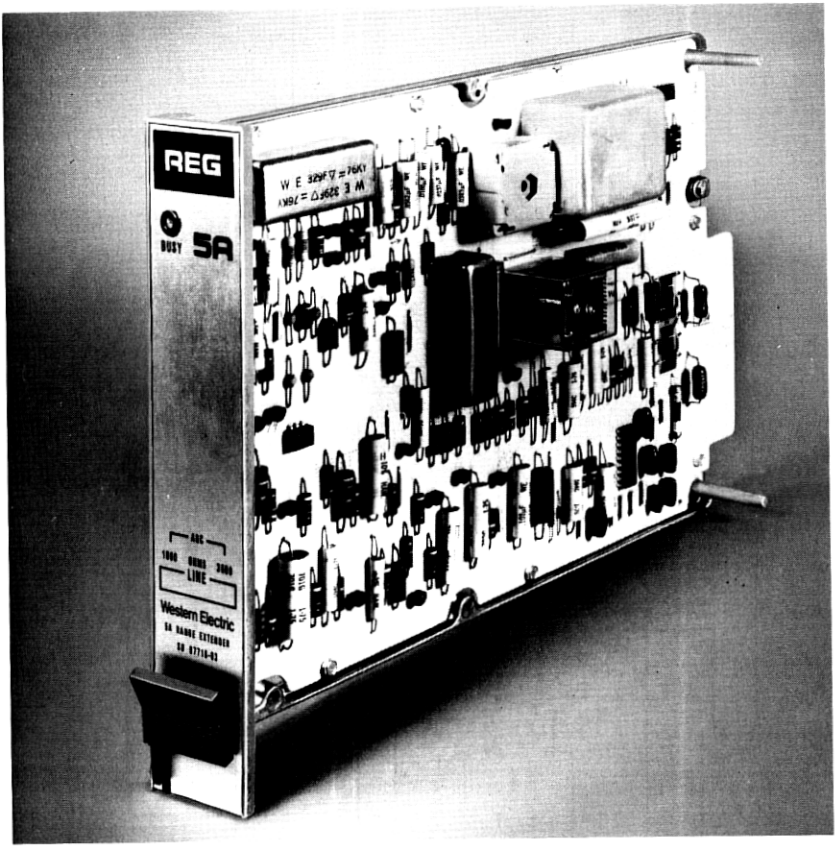


Fig. 19—5A REG plug-in assembly.

Besides use in Zones 18 and 28, it is seeing significant use in Zone 16 for ESS offices where transmission enhancement is wanted and in older No. 1 ESS systems where signaling enhancement is needed. Occasionally the REG is used in Zone 16 for crossbar systems where standardization on a single range extender is considered more important than the lower price of the 2A range extender that the REG supplants.

Operation of the circuit can be understood by reference to Fig. 20. The circuit configuration is controlled by two relays. The RO relay when operated places the amplifier and repeat coil in the loop. Otherwise the circuit is in a bypass mode with only a pair of 100-ohm resistors in series with the loop. The L relay repeats dial pulses around the repeat coil. The loop current detector is a high-impedance balanced bridge circuit that is basically immune to longitudinal loop currents. Upon call origination it senses the loop current in about 100 milliseconds, causes the L relay to operate, initially placing the 1000-ohm shunt across the loop, and then operating the RO relay to reconfigure the unit into the active state. The

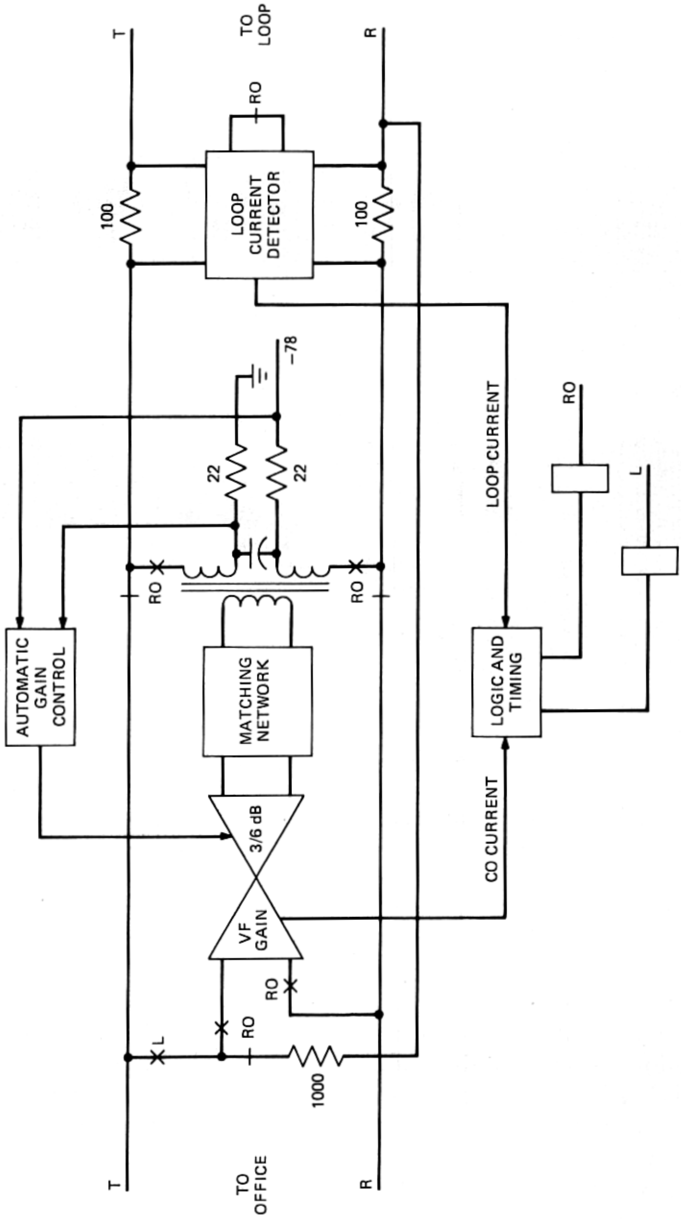


Fig. 20—5A REG simplified schematic.

office sees the low resistance of the REG amplifier and starts the origination sequence. RO relay operation also applies a 78-V boosted battery to the loop to aid dial pulsing and talking. Dial pulsing occurs in the active state and is repeated by the L relay. The logic and timing circuit regenerates the dial pulses and removes some distortion. A terminating call rings through the REG in its idle state. When idle, the loop current detector contains a low pass filter to inhibit pretrip which would otherwise occur due to the effects of ringing current on the detector.

When the office switch makes a tip party identification test, it breaks loop current. This break is sensed by an optical coupler in the amplifier which causes the RO relay to revert to the unoperated state. The L relay, however, stays up and completion of the tip-party test is sensed when returning office current flows through the 1000-ohm resistor and one side of the loop current detector. The RO relay is then re-energized, restoring the active state. The tip-party test is not aided by the REG, which is in the passive state during the test. All office circuits have the ability to perform this test unaided over 2800-ohm loops.

The amplifier gain is set by the AGC circuit. Loop resistance is determined by a comparison of loop voltage and loop current sensed at the 22-ohm series resistor. The amplifier is maintained in the 3-dB state for loops under 2000 ohms and during dialing and other transient states. The matching network maintains acceptable stability for all Bell System H88 loaded cables. Echo return loss is typically 15 dB, and worst case about 7 dB for loops such as those of Fig. 14. Singing return loss at the worst single frequency is typically 8 dB, and worst case about 2 dB. These values are better than for nonrange-extended loops.

VII. RINGING EXTENSION DEVICES

Boosting ringing voltage in the central office is not a practical way to extend ringing range significantly. The main problem is that voltages sufficiently high to appreciably boost ringing range are considered hazardous to personnel and would undoubtedly require costly changes in outside plant design and maintenance procedures. Fortunately other means exist to accomplish ringing range extension. A view of the problem is seen in Fig. 21. Here a ringer is connected between the ring lead and ground with the switch portion of a ringer isolator in series. A grounded ringer connection is shown, as this is necessary when more than three single party ringers are required or when serving party lines. The ringer isolator is shown generically and is used to represent a variety of Bell System devices including conventional cold-cathode gas tubes. Its function is to preserve line balance by keeping the ringer isolated from the line except when ringing voltages are present.

There are three parameters of this circuit under design control that affect ringing range. These are:

(*i*) The ringer isolator switch impedance R_s. For gas tubes this is

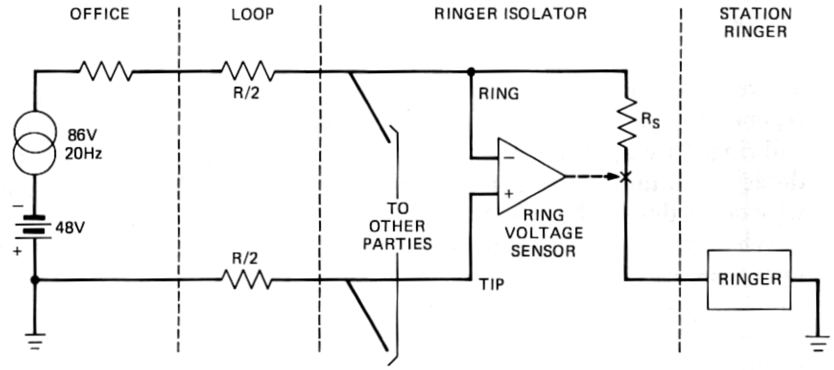


Fig. 21—Typical grounded ringing circuit.

a nonlinear impedance creating an essentially constant voltage drop of 70 volts. This is so great that a special low impedance ringer connection is required in order to preserve any significant ringing range.[14]

(*ii*) The ringer sensitivity. Ringers have a sensitivity adjustment. In low notch position a ringer will typically ring on about 35 volts. In high notch position the ringer requires about 50 volts. The high position must frequently be used to prevent crossring, the undesirable ringing of another party's phone. This phenomenon could occur, in Fig. 21, if the office were ringing the tip conductor and the tip party went off-hook during the ringing interval. The low resistance of the tip party's set would effectively short the tip and ring conductors, placing about 40 volts of ringing on the ring conductor and causing the ring party to ring until ringing was tripped at the office.

(*iii*) The ring voltage sensor threshold. The voltage across the ring voltage sensor is the sum of the ringer drop and the voltage drop across R_s. The sensor threshold must be below the sum of these voltages or it will limit the ringing range. With a low notch ringer setting and a small R_s the ring voltage sensor should threshold below 35 volts. Typical thresholds for ringer isolators vary from about 5 volts to roughly 65 volts.

An optimum ringer isolator is, therefore, one that has a negligible R_s, a ring voltage sensor threshold below 35 volts, and somehow allows ringers to be placed in the low notch without crossring. This latter objective can be met by a high R_s value which desensitizes the ringer but conflicts with the first two objectives. This approach is common in practice. A more elegant solution is to make the ring voltage sensor dc polarity sensitive. In the aforementioned example ringing the negative tip party will reverse bias the negative ring party's sensor and prevent

Table I — Ringer isolator performance comparison

Ringer isolator device	R_s or equivalent voltage drop	Ring voltage sensor threshold	Polarity sensitive	Ringer capacity @2800 ohms
Capacitor	0	No sensor	No	2*
D180036 Kit	2V	5V	No	2*
Gas Tube	65V	75V	Yes	1
11A Extender	10V	40V	Yes	4
28A Isolator	2V	30V	Yes	5

* Assumes ringer bias spring in stiff notch to prevent crossring on party lines.

crossring. Note the polarity sensitive sensor is used here only to prevent crossring and not in the usual sense to provide full selective ringing.

The degree to which existing devices meet the above objectives is indicated in Table I. The first three devices are older designs that mount inside the phone set.[19] Their ringing capabilities are limited because of deficiencies in one or more of the three critical design parameters. The last two devices, the 11A extender[14] and the 28A isolator have been made available in the past 4 years. Their improved performance is evident in Table I. Because of polarity sensitivity they can also be used for full selective ringing, thereby making them good general-purpose devices.

7.1 28A ringer isolator

The 28A isolator supersedes the 11A extender and is the current choice for Bell System party lines or long route single-party service requiring multiple ringers. It is shown in Fig. 22 in a typical mounting adjoining a protector block outside a house. The 28A isolator features:

Reliable solid state design
Mounting outside house
One unit serves all phones at station
Rings five phones at 2800 ohms
Polarity sensitive for selective party lines
Tolerates 150-V, 60-Hz induction
Causes no radio or TV interference
Unaffected by ringing voltage crest factor
Compatible with three-conductor house wiring
Compatible with 97-volt ringing
Will not pretrip ringing on short loops
Allows loop continuity testing without test desk modification
Small size—9 cubic inches
Low price—about half that of the 11A extender

VIII. CONCLUSIONS

The voice frequency range extension field extends several decades into the past and includes a large variety of range extension devices working

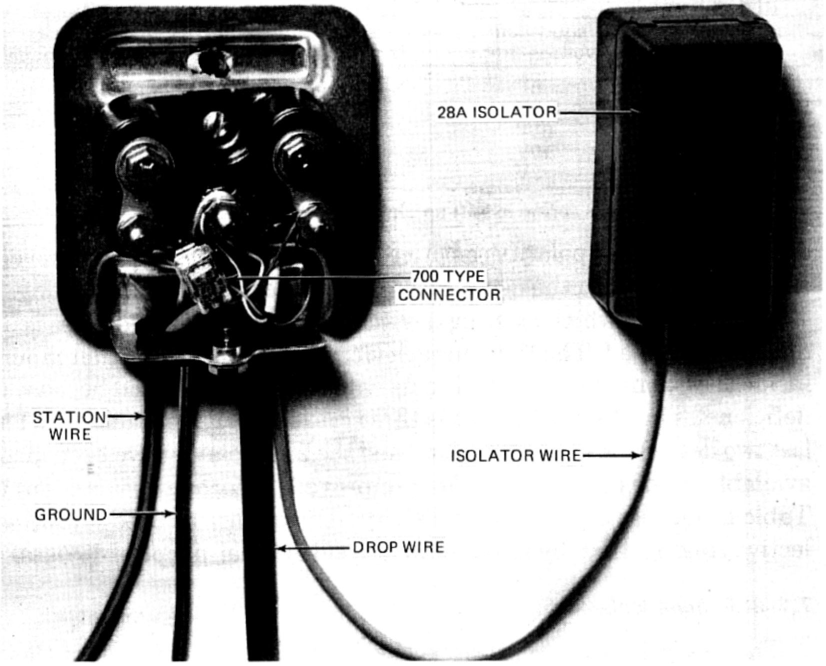


Fig. 22—28A ringer isolator mounted with station protector.

compatibly within the spectrum of Bell System central offices. In the last six years Bell Laboratories has mounted a concerted effort to define objectives for this range-extended plant, to design attractive low-cost range extension devices, and to provide features minimizing administrative and maintenance efforts. The 5A REG and the 28A isolator are the evolutionary products of this effort. Together they provide low-cost quality service to 2800-ohm loop resistance.

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