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Loop Plant Electronics:

Overview

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The dramatic improvement of semiconductors and other electronic components has yielded the low costs and high reliability long sought in electronic loop systems. The scope of existing systems includes range extension, analog and digital carrier, and loop switching systems. Use is accelerating and procedures are evolving to make such systems a fully accepted substitute for traditional cable pairs in telephone company operations.

The past ten years has been a period of intensive work in the application of electronics to the subscriber loop plant. The percentage of subscriber loops with some form of electronic augmentation is on a steep upward slope as a result of the combination of several major factors.

Most obvious is the fact that the costs of electronic alternatives to physical loop plant are coming down with each successive design generation. This, of course, parallels what is happening throughout the electronic equipment business, most obviously in the consumer market. At the same time, the costs of cable and associated construction and installation have been rising due to the pressure of material and labor cost increases.

The basic technological advance most responsible for lower cost electronics is the integration of analog and digital circuit functions into silicon semiconductor devices. The scores of discrete components formerly required to implement a function, such as companding, have been replaced with a single silicon chip with appropriate diffusion and metallization patterns. The attendant reduction in the number of components not only yields economies but greatly increased reliability as well. This is in striking contrast to the situation as recently as 15 years ago.

I. HISTORY OF LOOP ELECTRONICS

Looking back over the history of efforts to introduce electronics into the loop plant, one sees the recurring and allied problems of cost and reliability. The loop environment is much more challenging than the trunk environment in both respects, with the obvious exception of reliability requirements on underseas cables. For this reason, the loop network has not yielded to the application of electronics nearly as readily as the exchange and long-haul trunk network.

The most obvious difference between the loop and trunk situations is circuit length. Only since the early 1960s have carrier systems on exchange and toll trunks begun to prove in at distances less than ten miles. The length distribution of trunks is such as to offer a sizeable market for carrier beyond this prove-in distance and this has led to a long series of successful trunk carrier developments. On the other hand, the typical loop is about one or two miles in length and only about four percent of loops are longer than six miles. The capital expenditures that can be saved by eliminating copper pairs have not justified the cost of multiplexing except at the long distance extreme of the loop length distribution.

Rural loops long enough to support the cost of multiplexing to save pairs generally occur in small cross-sections. There is, therefore, little opportunity for achieving the economies of scale which have driven down long-haul transmission costs.

Any pair gain system used to serve subscribers must have one end located remotely from the central office. The cost of installation and operation of remote terminals must be taken into account in comparing such systems with the copper pair alternative. Reliability is an important consideration in loops where system failures mean loss of a customer's telephone service. Technology quite acceptable for trunks with both ends in central offices and with paralleling alternate routes may not be appropriate for loops. For example, electron tubes, which provided the basis for early carrier systems, were never suitable for large scale use in subscriber systems because of problems of limited life.

In spite of these difficulties, there have been continuing efforts to innovate in the loop plant, because the stakes were recognized as being very high. Much of the groundwork for loop systems was established in the years immediately after World War II but these systems were not really viable with the then available technology.

One of the earliest efforts involved the use of electric power distribution systems as the transmission medium for reaching remote rural customers. The M carrier system was introduced in 1945 and found limited use for this purpose.[1] The costs of getting carrier signals on and off high-voltage AC conductors and the difficulty of maintaining the integrity of the transmission path in the face of power company rearrangements caused this system to fall into disuse. Another early effort was the use of radio. This approach has been used since 1946 to serve remote customers. Costs, even today, are too high to support large scale use of radio, although this approach is under continuing review.

The next major effort to use the techniques of long haul transmission in loops came after the invention of the transistor. P carrier was the first system to use transistor amplifiers and was an early attempt to reduce the cost of serving rural customers.[2] This system was introduced in 1956 but found only limited use because of problems of costs, reliability of early vintage transistors and other newly developed components and the rigors of a hostile environment. In many ways, it served as the prototype for station carrier systems introduced by several manufacturers some 15 years later with a more mature semiconductor technology. The latest in analog loop carrier systems are described in this issue.[3] These are a single channel system for urban use (the *SLC*™-1 system) and a multichannel system, similar to P carrier, for rural use (the *SLC*-8 system).

At the same time that P carrier was being introduced, interest was turning to the newer field of digital transmission. Carrier terminals implemented by pulse code modulation techniques were found to be lower in cost than the then-existing analog carrier terminals. However, a much wider bandwidth was required to transmit digitally encoded speech signals. For example, a 24-channel PCM bank produces a 1.544 megabit digital signal for transmission between terminals to convey a total speech bandwidth of less than 100 kHz.

This apparently unfavorable bandwidth tradeoff is more than offset by the increased immunity to noise and distortion resulting from the use of low cost digital repeaters. Provided that the signal is fully regenerated at regular distances, typically 6000 feet on 22-gauge cable pairs, impairments do not accumulate enough to cause errors. There is, therefore, little degradation of transmission with length.

The T1 digital repeater, designed to receive and regenerate bipolar pulses at a 1.544 megabit rate, made possible low cost carrier transmission over cable pairs in existing exchange trunk cables. Digital transmission on these exchange trunk cables turned out to be very robust. It was an obvious step to consider the use of the same repeaters as the basis for systems on loop cables. The first such system (the *SLM*™ system) was introduced in 1972[4,5] and has since been superseded by the *SLC*-40 system, a more cost-effective second-generation system.[5] Digital transmission has now been firmly established as a viable technique in loop as well as trunk cables, opening up the future possibility of end-to-end digital transmission.

In parallel with early efforts to exploit carrier transmission techniques, switching solutions were also being studied. The most straightforward method is to remotely concentrate the traffic from nearby customers on a smaller number of trunks back to the serving central office. It is also possible to complete connections within the remote concentrator, but this is cost effective only when there is a high community of interest among the customers served.

Research of the late 1940s and early 1950s led to exploratory development attempting to use electronic techniques to build such remote concentration systems. These techniques had not matured sufficiently in the mid-1950s to provide an economically viable approach. A system based on electromechanical elements, designated the 1A concentrator, was introduced in 1962.[6] These concentrators found use primarily for the temporary deferral of the installation of cable in urban and suburban areas. However, they lacked the reliability, maintainability, and traffic administration features required for wide-scale use.

Exploratory development has continued in an effort to produce lower cost, more reliable systems that are easier to administer from a traffic standpoint. At the present cost of electronics, the use of such concentrators as permanent plant is viable, particularly in rural situations, and a modern system, the LSS, is described in this issue.[7]

This work on the application of transmission and switching techniques to gain the equivalent of more cable pairs in loop cables took place over a period of 25 years against a background of work to reduce the costs of cable pairs themselves. Lower costs were achieved not only through improved cable design and installation methods, but by the introduction of electronic techniques to permit the use of finer gauge wires.

Two broad system approaches have been introduced to reduce the required wire gauges through electronics. The Unigauge approach allows the use of 26 gauge pairs for all subscribers out to a 30 kft limit. Unigauge was implemented by range extenders behind the first stages of switching in No. 5 crossbar in 1969 and in No. 2 ESS in 1972.[9]

The second approach, Long Route Design, permits the use of 22 gauge and finer cable for loops as long as 82 kft. The introduction of Long Route Design coincided with the introduction of miniature Dial-Long-Line equipment and the 2A range extender, first manufactured in 1969. These miniature Dial-Long-Line equipments have since been largely superseded by a family of range extenders with gain (REG), introduced in 1972 to achieve lower overall costs of range extension.[10] The basic principles in REG have been subject to further refinement to reduce costs and simplify installation procedures and about one-half million have been delivered to the operating telephone companies. A concentrated version called CREG will supersede the Unigauge range extenders in ESS.[11]

II. EFFECT OF TECHNOLOGY IMPROVEMENTS

As stated in the introduction, no real progress was made in the introduction of electronics to subscriber loops before the advent of the transistor. Actually, it was an improvement of the whole family of electronic components including coils, capacitors and resistors as well as transistors which made possible the introduction of electronics in loops. However, had component technology not gone beyond discrete transistors and passive components, progress would have been very limited.

Today, the use of small-, medium-, and mainly large-scale integrated circuits pervades loop electronics products. The most dramatic effects of this IC technology is to be found in pair gain systems, whether analog and digital carrier or loop switching.

In the case of analog carrier, the pacing technology is bipolar custom linear integrated circuits. These ICs, typically involving 60 × 60 mil silicon chips, are capable of performing whole circuit functions; for example, modulation, demodulation, or companding. The single chips are the equivalent of hundreds of discrete transistors. Optimum ICs are not just discrete component circuit designs mapped into integrated circuit topology. Rather, the whole circuit design approach is changed to take advantage of completely different tradeoffs between the costs of passive circuit elements and transistor junctions. Furthermore, the junctions can be carefully matched in their basic characteristics through manufacture and they can be made to track very closely with the effects of temperature. This is fundamental to the improvement of performance over the earlier discrete component designs of functional circuits.

In the case of the companding function, a single chip, implementing a novel circuit approach only practical with integrated circuits, performs the functions of compression or expansion of speech signals depending on an external connection option. This IC compandor, used in both the *SLC*-1 and *SLC*-8 systems, goes well beyond the long-established performance objective for trunks with regard to signal distortion, control of channel loss, and speed of response. And yet, the two silicon chips and a number of discrete resistors and capacitors now replace a complete circuit pack in N2 carrier. The N2 system was introduced in 1962 on the basis of discrete transistors and passive components.

Digital carrier systems, too, are based on the extensive use of custom ICs. In fact, such applications occurred first because the digital IC technology was generally well ahead of analog IC technology.

The SLM system, 1972 vintage, was based on the use of custom MOS devices combined with thin film resistors on ceramic substrates. Today, digital bipolar devices with large scale integration as well as MOS devices are found extensively in loop pair gain systems. In fact, such devices are so solidly entrenched and accepted for these digital applications that little is said explicitly about the device technology in the system descriptions found in this issue. The use of ICs in digital systems has ceased to be at issue.

The LSS system includes a functional unit only possible with today's IC technology and this is worth special emphasis. That functional unit is a microprocessor. In LSS, the microprocessor is used to implement stored program control of the system at the central office terminal. The microprocessor used is PROCON, manufactured by the Western Electric Company. This particular microprocessor uses 8-bit data and 24-bit instructions and has a two microsecond cycle and instruction execution time. To control LSS, 5700 words of read-only memory (ROM) and 512 words of random-access memory (RAM) are required.

Of the 5700 words of ROM, only 2000 are used for call processing. The remaining two-thirds are required for automatic trouble location, manual testing, alarms, and traffic measurements. These are functions which would be hardly practical without the stored program control approach. With electronic sophistication, it is possible to make today's systems fit much better into the telephone company environment. LSS succeeds where earlier line concentrators failed in this regard.

III. FITTING THE ENVIRONMENT

Important work has been done to better fit the physical environment of the loop distribution network.[12] While much clever design has been carried out to reduce the costs and improve the appearance of the central-office-mounted parts of the product line, the primary challenge is at the remote terminals.

Physical designers have had to cope with the harsh environmental extremes of North America for products ranging from a 2 cubic inch isolation filter to a 16 cubic foot *SLC*-40 remote terminal. Because of these great differences in size and differences in internal heat dissipation, there is no universal solution to the design of outside housings.

The *SLC*-8 system, having a small modular size and no batteries and battery ventilation, has offered the opportunity for the most innovative approach. In this system, plastic moldings enclosing 8 subscriber channel units nest into standard outside plant closures. The need for unique construction procedures for installing the system are avoided, a major step toward eliminating the special nature of loop electronics.

Until the recent generation of systems, loop electronics fit only into very special situations: on very long routes, at locations of rapid growth of service demand, or in areas of extremely high construction costs. There was no great difficulty in identifying applications in trailer camps and at river crossings, and the economic advantages were usually quite obvious. It was quite practical to install and maintain systems on a special engineering and maintenance basis when quantities were limited.

Today's lower costs offer the potential of much greater penetration and more widespread savings. However, this is not going to happen unless these systems enter into the main stream of telephone company engineering and operations.

First, and most obvious, is the fact that the systems must have the right features and parameters to fit the telephone company needs. This is particularly important from the standpoint of the craft personnel who must operate and maintain loop facilities. Equally important is the development of fully documented methods for planning, engineering, installation, and maintenance.

While much remains to be done to achieve full compatibility with the management of more traditional telephone plant, significant progress has been made in cooperation with AT&T and the operating telephone companies to establish workable procedures for planning, engineering, maintenance and administration.[13,14] Most of the work so far has been in the context of rural applications where loop electronics has found its first application because of the high cost of traditional plant construction methods.

The planning and engineering process begins with the recognition of a need to satisfy a service demand either present or forecast. Once this need and the limitations of the existing plant have been characterized, broad guidelines can be used to determine what alternatives, from the wide range of systems available, are worthy of more detailed studies. Depending on the complexity of the particular problem and local preferences, these detailed studies can be carried out either manually with well-established step-by-step procedures or by time-shared or batch computer programs. The net result of this work is a fundamental plan for satisfying the service demand in an optimum way.

These methods are well advanced for the analysis of rural applications, though work continues on unification and simplification of procedures. The developers of these methods have had available a good characterization of the rural environment in the long route data base assembled by AT&T. Furthermore, in these rural applications, capital cost is a dominant factor and the necessary cost parameters are relatively easy to obtain. Capital cost is also a dominant factor for temporary applications where major plant construction can be deferred in suburban areas. Achieving a similar capability in the optimum use of loop systems in suburban areas is the subject of on-going studies. Here, the impact of the systems on the cost of operations is a much more important factor.

In examining the maintenance and administrative aspects, it is helpful to compare loop electronics carrier channels with the feeder cable pairs which they replace. Methods and procedures being recommended are gradually leading to a full acceptance of that approach.

An example of a recommended procedure is the trouble-shooting of a single channel failure in a subscriber carrier system. In the event that such a failure occurs in a *SLC*-40 system, an installer-repairperson dealing with the trouble should transfer service to a spare channel in the *SLC*-40 just as he or she would transfer to a spare feeder cable pair. The change-out of a faulty *SLC*-40 plug-in should be the responsibility of craft more experienced in the maintenance of the carrier system. This is analogous to feeder pairs being fixed by cable repair forces, not by installer-repairpersons.

Admittedly, much about the operation of loop electronics is still considered special and dealt with by methods outside normal procedures. To a large extent, this is a holdover from past practices which have not yet been changed. For example, it has long been customary for electronic equipment of any kind to terminate on the horizontal terminal blocks of the main distributing frame. On the other hand, if subscriber carrier channels are to appear like feeder cable pairs, they should terminate on the vertical side along with the feeder cable pairs. Through cooperative efforts of Bell Labs, AT&T, and the operating telephone companies evolutionary problems like these will be solved. It is both timely and necessary to make these changes because the costs and reliability of loop electronics today support use of these systems as a substitute for cable pairs on a wide scale basis.

IV. PRODUCT LINE CONSIDERATIONS

The equipments described in this series on loop electronics constitute a complete product line. That is, all the known and significant systems approaches for loops are matched by members of this set of products or combinations thereof. Each product has areas of application where it is more effective than the other products in reducing capital costs. These primary areas of application are summarized in Table I.

Of course, these categories may appear more disjoint than they really are. Economic studies of the kind previously discussed can resolve most issues of application, but "gray" areas will still exist. For example, a cluster of six *SLC*-8 systems will give a cost per pair gain comparable to a *SLC*-40. In cases like this, choices will have to be made on the factors other than cost. Some important factors are listed in Table II for *SLC*-8, *SLC*-40, and LSS. Different companies are likely to give different weight to these factors based on local service conditions.

Table I — Primary applications

System	Primary application areas
REG	Fringe suburban and rural areas
CREG	High-growth suburban areas
SLC™-1	Mature, but changing, urban and suburban neighborhoods
SLC-8	Distant, low-density rural areas
SLC-40	Distant, clustered rural areas
LSS	Suburban areas with high construction costs and rural areas with low pair gain ratio requirements

Table II — Factors affecting choice of systems

	SLC™-8	*SLC*-40	LSS
Transmission	Analog	Digital	Voice Frequency
Repeater spacing	4 miles	1 mile	None
Channel/trunk test	Loop-back	None	Automatic
Drop test	None	None	Unlimited
Drop length	400 ohms	900 ohms*	1700 ohms†
Power reserve	Powered from CO	8 hrs	Powered from CO‡
Pairs gained	7	36	62
Pairs required	1	4	34
Pair gain ratio	7	9	1.82

* 1600 ohms under special circumstances.

† The total resistance from the central office to the customer cannot be more than 2800 ohms, with range extension applied to the trunks for resistance greater than 1600 ohms.

‡ Pair resistance greater than 2800 ohms from the central office to the remote terminal requires a remote power feed.

For example, consider an area where there is heavy emphasis on the ability to apply all existing methods for testing metallic loops all the way to the customer's ringer. Consider a further need to survive power blackouts longer than the nominal 8-hour reserve of back-up batteries in remote terminals. LSS is the obvious choice provided the existing cable cross-section is adequate for the application, and it is not necessary to gain the transmission improvement of analog or digital carrier. *SLC*-8 permits convenient modular growth and is completely powered from the central office. On the other hand, *SLC*-8 has a more limited drop range than *SLC*-40, and it uses analog line transmission, an approach less compatible with the long-term trend to a digital network.

This discussion simply illustrates some of the hard choices to be made. It is recognized that local preferences and the desire to standardize on a subset of available systems in a given operating area may cause the bending of strictly economic decisions. We continue to strive for a single, unified system approach with the best features of the present diverse product line. Unfortunately, that perfect system has not yet arrived and cannot be firmly predicted. There are, however, some very clear trends for the future.

V. FUTURE TRENDS

The future will see the introduction of pair gain systems far cheaper than anything available today. For example, it is likely that by 1979 the effective installed cost will go down by about 2:1. There is a further prospect of reduction in cost through integration of digital loop systems with an overall digital network plan. This will continue the very steep downward trend that has been experienced over the past two years.

One of the consequences of lower costs will be a greatly increased penetration of electronics into the loop distribution network. Today, loop electronics of all kinds are applied to about 2 percent of Bell System growth lines. If the kinds of cost reductions predicted above are actually realized, this penetration of growth lines will increase tenfold. The use of such large quantities of electronics in the loop plant will place increased emphasis on size and power reductions. This large penetration also means that the cross-sections of digital transmission over the three or four major feeder routes of a wire center will become very large, in excess of several thousand speech channels. This may well afford the best opportunity for introducing optical fiber transmission into the loop plant. Optical fibers, with their high speed capability over long repeaterless spans, may be the only viable way to deal with this greatly increased penetration of digital transmission. Of course, once fibers are introduced to support existing telephone and high speed digital services, there will be the further possibility of adding video bandwidth services in a very graceful manner. New services are likely to be a very important factor in the future of loop electronics development. A similar review ten years from now will most probably present an impressive picture of expanding services as well as reduced costs.

REFERENCES

1. J. M. Barstow, "A Carrier Telephone System for Rural Services," Transactions of the AIEE, *66* (1947), pp. 501–507.
2. R. F. Clark, "Transistorized Rural Carrier System," Bell Laboratories Record, August 1956, pp. 281–284.
3. T. N. Rao, "Analog Loop Carrier Systems," B.S.T.J., this issue.
4. I. M. McNair, Jr. "Digital Multiplexer for Expanded Rural Service," Bell Laboratories Record, March 1972, pp. 80–86.
5. G. A. Nelson, C. H. Sharpless, and M. T. Manfred, "Digital Loop Carrier Systems," B.S.T.J., this issue.
6. M. E. Krom, "The 1A Line Concentrator," Bell Laboratories Record, September 1962, pp. 297–302.
7. N. G. Avaneas and J. M. Brown, "The Loop Switching System," B.S.T.J., this issue.
8. L. R. Pamm, "Unigauge—A New Subscriber Loop System," Bell Laboratories Record, September 1967, pp. 261–264.
9. H. J. Beuscher and C. W. Deisch, "No. 2 ESS Unigauge Range Extension," IEEE Transactions on Communications, *COM-21,* No. 4 (April 1973), pp. 271–277.
10. J. C. Burgiel and J. L. Henry, "REG Circuits Extend Central Office Service Areas," Bell Laboratories Record, September 1972, pp. 243–247.
11. G. T. Hawley and K. E. Stiefel, "Voice Frequency Electronics for Loop Applications," B.S.T.J., this issue.
12. R. W. Henn and D. H. Williamson, "Loop Electronic Physical Design Considerations," B.S.T.J., this issue.
13. J. G. Schatz and M. A. Schwartz, "Planning for Loop Electronics Systems," B.S.T.J., this issue.
14. D. H. Morgen, "Maintenance and Administration of Loop Electronics," B.S.T.J., this issue.