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Volume 42 **1967** **Number 3**

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This Issue in Brief

Artemis, An Experimental Electronic Telephone Exchange—Equipped initially with 800 lines, the experimental telephone exchange, Artemis, was installed in the plant of Le Matériel Téléphonique in Boulogne to serve as a private branch exchange for that company and as an integrated part of the Paris public telephone network. It uses sealed reed contacts with remanent magnetic latching. Supervision is by programs permanently stored in a multiregister that provides centralized control. Only for reliability, the multiregister is duplicated.

The recorded programs provide for and recognize the different needs of the extensions of the private branch exchange and of the lines of the public network. They also provide for interconnection with other types of switching systems found in the Paris network.

Each multiregister is capable of controlling the entire exchange. As it cannot wait for the relatively slow operations of switching and signalling, it directs various electronic circuits to handle these functions and report back when they have been accomplished.

Microminiature High-Frequency Transmitter-Receiver—A mobile radio transmitter-receiver is described that operates between 2 and 30 megahertz for voice modulation with either single sideband or carrier and double sideband. The basic unit produces 7 watts for transmission, and amplifiers to increase this to 100 or 400 watts are available.

A frequency-generating unit produces a 4-megahertz wave from a temperature-controlled quartz crystal. By multiplication and by division it produces 28 megahertz and 1 megahertz for heterodyning, and 10 kilohertz as a reference frequency. Inductance-capacitance oscillators produce any desired frequency between 11 and 35 megahertz. This frequency is acted on by an adjustable frequency divider to give 10 kilohertz, which is compared with the 10 kilohertz derived from the crystal oscillator to produce an error signal to stabilize an inductance-capacitance oscillator.

The adjustable frequency divider converts the sine-wave input from the controlled oscillator into square-wave pulses that are counted in a binary chain. When all the stages in the binary chain assume the 0 or 1 values established by the frequency controls that set the divider ratio, an output pulse is produced, the chain is reset to zero, and a new count starts. These output pulses will then be at the 10-kilohertz frequency.

Varactors, voltage-controlled diode capacitors, are used to tune a single set of circuits that couple the antenna either to the receiver or the transmitter. They are also used for the controlled oscillators so that tuning is accomplished with control voltages between 10 and 100 volts.

Design of Medium-Speed Data Transmission Systems—Measurements and computations were employed to develop design principles for medium-speed data systems.

The logical assumption that errors would increase when the receive level falls below a certain threshold was confirmed. More errors occur when using switched connections than for leased connections. Noise disturbances tend to be of short duration and produce single errors independent of the signalling speed whereas transmission interruptions are usually of longer duration, the number of errors increasing with signalling speed.

Parity bits, even 2 per character, are inadequate but the use of a signal quality detector will improve detection of multiple errors. However, better protection is obtained with row-and-column checking. Cyclic codes for checking produce less redundancy and can provide any desired degree of protection. They are suitable for blocks of 100 or more bits but not for a single character of fewer than 10 bits. Blocks of 250 bits are not suitable for very short messages. For typical national toll connections with duplex operation over loops of normal propagation time, a block of 240 bits provides a reasonable compromise. Such a block can be protected by only 12 check bits in a cyclic code but would need 4 times as many for row-and-column methods and 6 times as many on a per-character basis. The sequential numbering of blocks ensures their acceptance in proper order.

***GH 205* and *GH 206* Medium-Speed Data Systems**—The *GH 205* (both-way) and *GH 206* (either-way) data transmission systems employ automatic error detection and correction techniques. They are capable of operating at speeds up to 1200 bauds with a variety of input/output devices.

Transmission is in blocks of 256 bits of which 240 represent information content, 12 are for protective redundancy, and 4 are service bits. The cyclic coding uses a protective polynomial of $X^{12} + X^7 + X^2 + 1$ to give an average improvement factor of 15 000.

These systems are compatible with the modem interface recommendations of the International Telegraph and Telephone Consultative Committee (CCITT). They have been operated over a wide variety of national and international circuits including satellite links.

Pulse Code Modulation for Automatic Switching of a Military Network—A military tactical telephone network should permit combat-zone units to be automatically interconnected regardless of their location or partial destruction of the network.

Pulse code modulation permits useful communication with a signal-to-noise ratio of only 10 decibels, a substantial improvement over analog transmission. The use of wide-band transmission highways with time-division channels allows very rapid signalling.

A mesh network in which each exchange is connected to several adjacent exchanges is used. A call placed through one exchange is transmitted to all other exchanges connected to the originating exchange. Each receiving exchange compares the called number with all of the numbers connected to it, which are written in an electronic memory. If the number is found in the memory, a reply goes back over the path through which the call was received and the connection is made. Otherwise, the exchange that does not have the called number sends it on to all other exchanges connected to it. In this way a call propagates throughout the entire network until it reaches the exchange serving the called line. A breakdown in any part of the network will be bypassed, thus insuring service under conditions of network damage. In a network of useful size, about 200 calls can be processed per second so that blocking is not important despite the many paths over which each call is sent to find the destination.

Numbers may be assigned to any exchange as they do not signify a direction from another calling exchange. They need only be written in the electronic memory of the exchange to be available for service.

Entraide Networks Combined with Link Systems—A link system with entraide is one in which some outlets from a given switching stage are connected to inlets of the same stage or of a preceding stage. If no direct path is available from the inlet of a matrix to a desired outlet, the entraide connection permits a path to be found through usable inlets and outlets in another matrix of that stage.

A practical example is given of such a stage with its geometric arrangement and the path hunting rules. The equations for dimensioning such networks are given. Calculations involve traffic handled without entraide assistance, overflow requiring entraide, all possible paths with and without entraide, and final blocking limits. Estimates are required for some of these factors.

To check on the calculations, a roulette model of simulating traffic used a pseudo-random number generator to establish independent call attempts and releases. Confidence intervals were determined by Student's t distribution. Tables of the results of the simulation confirm the practicability of the calculations.

Potentialities of an Integrated Digital Network—The article reviews very briefly the technical basis, performance, economic gains, and general feasibility of a comprehensive network based on the class of digital transmission established by the introduction of pulse code modulation. It is shown that such a network is attractive, not only for telephony, but also for data, text transmission, and other non-voice modes. A background is provided for subsequent discussion in greater depth of the various aspects of a theme that is likely to become increasingly important.

Dispersed Telecommunication Network Structure—The dispersed telecommunication system outlined permits telephone and other exchanges including concentrators to be located conveniently to the subscribers being served by them. These exchanges are controlled by computers remotely located and much fewer in number so the computers can be economically large. Where convenient, small computers may serve the exchanges and be served themselves by the larger computers.

Although a computer may serve several exchanges, each exchange will be connected to two or more computers to provide for reliability of service. The alternative computers will be sufficiently well informed to permit one of them to complete the functions of the operating computer in case it fails. The use of large computers will permit the operation and organization of the networks to be homogeneous while the techniques used for implementation are heterogeneous.

Data links using digital transmission will interconnect computers and exchanges to handle all supervisory and control traffic. The amount of digital supervisory traffic is well within the present-day data transmission capabilities.

Call Routing Strategies in Telecommunication Networks—An attempt is made to classify different strategies that could be used for routing calls through a communication network. This classification involves the stochastic nature of the strategies, their time dependence, range of action, network occupation dependence, cost, and quality dependence. Optimization criteria are then discussed in terms of traffic handling capacity, blocking requirements, and sensitivity to overload.

A comparison is made between several routing strategies in a very simple communication network. The results obtained by simulation are compared with approximate calculations.

Propagation in Periodically Deformed Circular and Rectangular Waveguides—Traveling-wave tubes must employ waveguides capable of propagating a wave having a phase velocity substantially less than the velocity of plane waves in vacuum. For such a guide, one wishes to know the phase velocities and electron beam interaction impedances of the various waves associated with each mode of propagation. These quantitites must, in general, be derived from a field analysis of each type of structure.

Although few mathematically tractable general methods exist for the analysis of periodic waveguides, such a method is developed by the author for the case where the guide wall is a periodic surface of revolution. This method is given in detail as it applies to a circular guide with a sinusoidally rippling wall, and approximate relevant velocity and impedance equations are derived from the field expressions obtained.

Approximate field expressions, based on a perturbation technique, are also given for a periodic guide of rectangular section. Particularly simple expressions are obtained for phase velocity and impedance, and the method may be applied to any rectangular waveguide mode. This guide, particularly, offers promise of usefulness for certain wide-band power traveling-wave amplifiers.

Artemis, An Experimental Electronic Telephone Exchange

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1. Introduction

Artemis is an experimental telephone exchange, of the space-division type and with electronic control, developed by Le Matériel Téléphonique under the sponsorship of Socotel (Société mixte pour le développement de la technique de la Commutation dans le domaine des Télécommunications), which organization includes the French Telecommunications Administration and the main French manufacturers of telephone switching equipment.

The use of crosspoints with sealed contacts and magnetic latching as well as centralized control with stored program, called a "multiregister," in duplicate for reliability, are the two principal technical characteristics. The multiregisters were derived from those that the CNET (Centre National d'Études des Télécommunications, Département Recherche sur les Machines Electroniques), studied for the experimental exchange, Socrates. They were developed and manufactured by the Socotel Common Laboratory at Lannion. The switching network, electronic assemblies, programming of the multiregisters, installation of the exchange, and testing of the whole were the responsibility of Le Matériel Téléphonique.

Equipped in the first phase with 800 subscribers' lines, the Artemis automatic exchange is intended to serve the internal traffic of the facilities of Le Matériel Téléphonique at Boulogne. This use as a private exchange has the advantage of actual operation on important subscriber traffic of a design conceived for public exchanges of up to 30 000 lines. To study the problems of interconnecting an electronic-controlled exchange with existing networks, during an experimental phase, the private exchange will serve as a part of the public exchange, being given a prefix of 3 digits similar to other exchanges of the Paris network. The subscribers of this test network will then be able to call the telephone network of Paris or be called through it with 7-digit numbers and communicate in both directions with the national network with 10-digit numbers.

In practice, the functions of the private and public exchanges are mingled and their subscribers are connected to the same switching network. The multiregisters possess two sets of programs, one corresponding to the public exchange and the other to the private exchange. According to the category of the calling subscriber or of the incoming junction, the multiregisters identify the kind of service required, either public or private, and initiate the corresponding program.

2. Description of the Exchange

2.1 General Structure

Artemis comprises two main sets of apparatus, the switching network and the multiregisters. The fundamental role of the switching network is to ensure the metallic connection between a subscriber's line and the junctors; the multiregisters perform the functions of control, registering of the called number, translation, and charging.

It is not advisable to concentrate all the control functions of the exchange in the multiregisters. The connection of a subscriber to a junctor, for example, requires 1 or 2 milliseconds whereas the operating speed of the multiregisters is so much faster that they should not be held for this length of time. Buffer registers receive orders from the multiregister to control the operation of the crosspoints and report back to the multiregister that the order has been correctly carried out.

Other functions are carried out by electronic circuits associated with the switching network. To establish a connection inside the network it is necessary to check the availability of the network links. This link availability information could be kept in memory in the multiregisters, but this entails two difficulties. The first is that the multiregisters each handle different calls. Having established or released a connection, each multiregister would have to supply this information to the other multiregister, which would entail considerable traffic between the two multiregisters. The second difficulty in keeping link availabilities in memory is due to the accidental mismatching that can occur between the real condition of the network and the condition of the memory. The solution chosen has been to assign to the switching network the function of testing for link availabilities, then to add to the two speech wires a third wire the function of which will be discussed later.

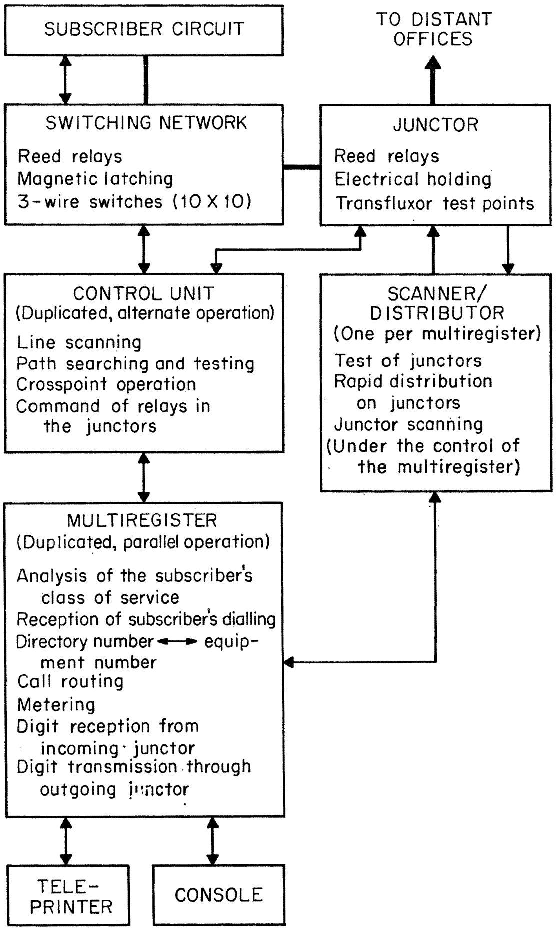

Figure 1—General arrangement of Artemis exchange.

Figure 1 shows the broad structure of Artemis and the distribution of functions among the different units.

2.2 Multiregister

2.2.1 *Memories*

There are three different kinds of memories in the multiregisters.

(A) A semipermanent memory of woven cores is provided for the stored program. This memory has a capacity of 4096 words of 32 bits. Each word contains a "directive," itself made up of three orders, 01, 02, and 03 (see Figure 2). Each order uses 8 bits providing for 256 different orders. In addition to the 3 orders the directive comprises a code *S* of 3 bits; this code is followed by a sign and indicates the address step to be performed in passing to the following directive. This step has an amplitude between -7 and $+7$ and can be made conditional if the directive contains one or more test orders. The 3 orders of a directive are always performed in sequence during 40 microseconds of which 16 microseconds are for the address progression, the extraction of the directive, and the different controls, and 8 microseconds are for each of the 3 orders.

(B) A temporary memory uses ferrite cores to be read by coincidence of currents. Its capacity is also 4096 words of 32 bits and the cycling

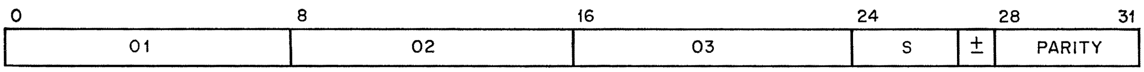

Figure 2—Constitution of a 32-bit word of the semipermanent memory of the multiregister.

time is 5 microseconds. This memory has two different uses; the first half records temporary information concerning communications being established or released, information on supervision of established communications, and certain tables. The second half is for certain programs; such as for testing, diagnosing, and programming. These programs are introduced and retained only for the time they are required. This part of the memory is protected against erasure while the programs are being executed.

(C) A magnetic drum memory of 16 384 words of 32 binary elements, which has a mean time of access of 10 milliseconds, holds all the information that it is not economical to put into the core memory. Here are found mainly the subscribers' classes of service, subscribers' meters, routing tables, and abbreviated numbering. It is never necessary to have very rapid access to this bulky information. The magnetic drum also stores the special programs mentioned in **(B)** that are read from temporary memory according to need. Lastly the drum contains a duplicate of all the information necessary for the automatic restarting of the multiregister after trouble by a simple reading from the drum of the necessary information.

2.2.2 *Logic*

All the memories are designed for words of 32 bits. Traffic with peripheral equipment, such as the control unit of the network and the explorer, is by 32-bit words in parallel. As shown in Figure 3, the multiregister has a set of transfer bus bars for parallel transmission of 32 bits via the memory registers L and R for the temporary memory and I for the drum or between these registers and the peripheral equipment. The arithmetic block at the left comprises mainly 3 registers, X, Y, and Z, and circuits allowing partial erasure, shifts, and arithmetic operations to be carried out on the content of these registers. This arithmetic block does not manipulate complete words of 32 bits, but only blocks of 10 bits for which appropriate bus bars are provided.

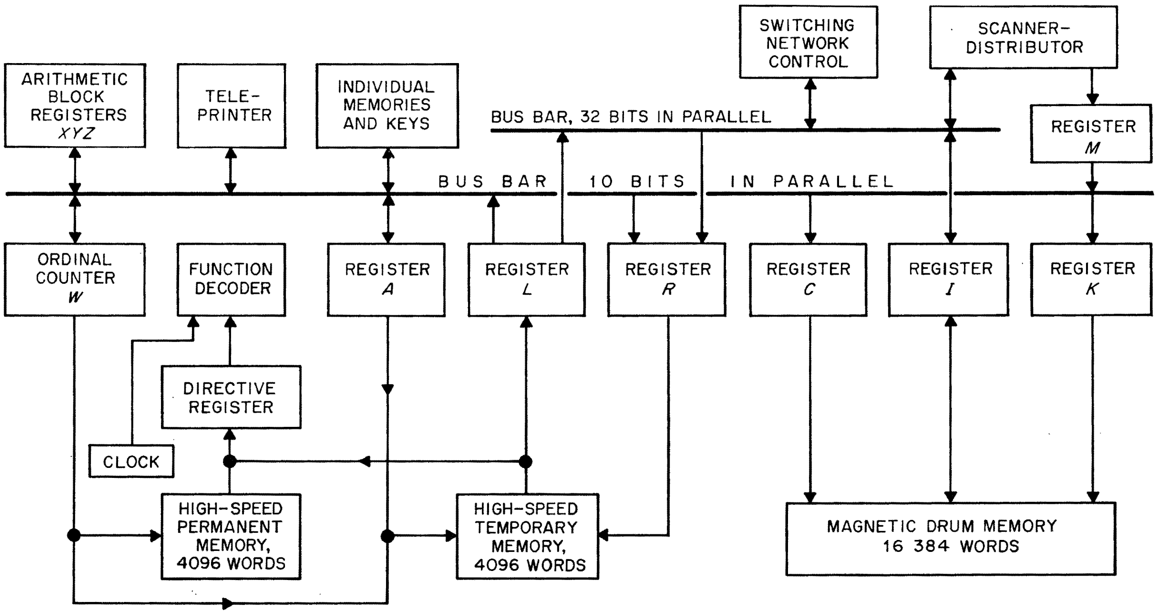

Figure 3—Logic of the multiregister.

The magnetic drum is directed by two registers: register K gives the number of the track among 128 and register C gives the angular address, also among 128. The temporary memory is directed by register A of 9 bits. As a complete address of the temporary memory requires 12 bits, the 3 complementary bits are given by the order. In other words, it can be said that for the execution of an order of memory reading or writing, the A register designates a sector of 8 words and the order makes precise the word of this sector. This very simplified system of indexing is very convenient, considering the problems to be treated in an automatic exchange. For each communication in use a zone of 8 consecutive memory words is reserved (each such zone is called a "register"). During the initial assignment of a register, its address is written into the A register, which then acts as index register for the orders for reading or writing words in the register.

The program is advanced by an ordinal counter W, containing at each instant the address of the next directive, which address is in a semipermanent or temporary memory. Each directive requires that 3 orders be carried out sequentially. However, the sequence of the directives is very flexible, the code S of Figure 2 allows a sequence from -7 to $+7$ conditional on the directive containing at least one test order. Lastly, a sequence of greater amplitude is possible by means of a break-sequence register.

2.2.3 *Outgoing Connections*

The multiregister has access to the control unit of the network by means of a 2-way 32-bit channel connected to the 32-bit bus bar. This is also used for connections with the explorer, but in addition there is a supplementary return channel connected to the 10-bit bus bar to send back the results of the junctor tests.

The multiregister communicates with operating personnel by teleprinter. A central control desk has facilities for starting the multiregisters and peripheral equipment, maintenance operations, trouble diagnosing, et cetera. In principle this desk is used only when maintenance personnel must intervene in the operation of the exchange.

2.2.4 *Principles of Programming*

The multiregister is capable of performing various general logic functions but must be programmed to control an automatic telephone switching system. This program, stored in several memories, consists of instruction lists that determine the sequence of operations. The major functions are given below.

Scanning of incoming junctors to detect calls.

Supervising detected subscribers' calls.

Analyzing the category of calling junctors or of subscribers.

Controlling connections in the network.

Registering the number of a called subscriber or of the signals received on incoming junctors.

Translating the prefix and number of a called subscriber.

Sending signals to outgoing junctors.

Supervising established communications.

Charging.

Recording trouble information, network congestion, and traffic statistics.

Although the multiregister simultaneously processes a large number of telephone calls, it does not work exclusively on each call until it is completed but leaves each call after it has directed the next operation and returns later when that operation has been completed by slower-operating devices. For each call the multiregister is clearly obliged to assign a zone of its temporary memory to register all the information concerned with its progress. This information includes the number and category of the caller, number of the numbering junctor, received digits, category of the called subscriber, number of the junctor chosen for the call, the number of the sender, et cetera. This memory zone is called a register, and stores 8 consecutive words of 32 bits.

The multiregister deals cyclically with all the registers in two distinct cycles; one of 10 milliseconds and the other of 200 milliseconds.

2.2.4.1 *The 10-Millisecond Repeated Program*

The multiregister consults each register to handle the next step required to advance the call being processed. Thus, if this call is for example in the state of receiving a subscriber's number, the multiregister notes the state of the subscriber's loop to detect a possible change of state thereof (pulse start or pulse end). If no change has occurred the multiregister advances a counter in one of the register words. If this counter overflows, it indicates that a predetermined time has passed since the last change of state and this indicates either an end of the train of impulses or that the subscriber has placed the handset on the hook terminating the call. If there has been no change of state or overflow of the counter, the multiregister leaves this register and passes to the following register. This processing time is very short (80 microseconds). If a change of state is detected, the multiregister initiates the next processing step and this may take 120 to 500 microseconds. This is called the rapid program.

The multiregister spends a very large proportion of its time in the rapid program in scanning the registers, which determines the capacity for operations. Thus, in Artemis, the time of minimum processing being 80 microseconds, the multiregister can process 10 000/80 = 125 registers as a maximum. Actually the number is smaller because additional tasks also require processing time.

2.2.4.2 *Scanner Control Program*

The scanner program controls the junctors and auxiliaries on which calls have been made and surveys the calls appearing on incoming junctors. This scanning is done in a period of 50 milliseconds. To establish this period the previous cycle of 10 milliseconds is used and in each such cycle one junctor out of five is scanned. The multiregister stores the condition of all the junctors and sends this information in sequence toward the scanner, which compares it with the present condition. If a difference is noted, the scanner makes a call toward the multiregister. A register will ultimately be assigned to carry out a more-precise analysis of the change. The control scanner program occupies the multiregister for 1 millisecond out of every 10 milliseconds.

2.2.4.3 *The 200-Millisecond Repeated Program*

The complex and nonurgent operations, such as analysis of received digits, long delays, charge calculations, et cetera, are not carried out in the rapid program. These tasks are carried out in the free time at the end of the cycle for the rapid programs (see Figure 4). The multiregister processes sequentially a certain number of registers by performing the required long tasks until it is interrupted at the end of 10 milliseconds. In the course of a cycle, this program (called the slow program) can process only a small number of registers. But after a certain number of consecutive cycles all registers will have been served and the program will be able to return to the first register.

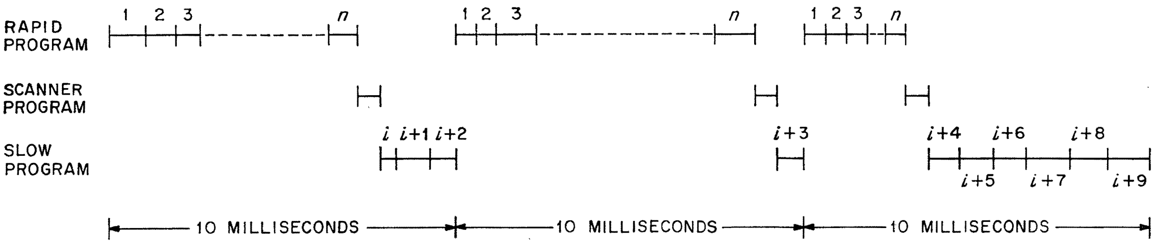

Figure 4—Time relation of programs.

The return to the first register is controlled by a second clock, regulated to 200 milliseconds. In so far as this time has not been reached, the multiregister carries out routine programs having no urgency, such as systematic tests, establishment of statistics, et cetera.

2.2.4.4 *Philosophy of Combining Programs*

Different tasks are performed with 3 degrees of priority (rapid programs and scanner control programs, slow programs, and routine programs). A master timing device to fit these programs together has not been provided as the fitting of all the programs into small subprograms was considered sufficient. This system operates with very simple circuits and the processing is very easy. The small restriction imposed is not inconvenient for in telephone switching the dividing of work into small elements occurs normally, a new element of work having to be performed at each new event (arrival of a call, receipt of a digit, termination by the called subscriber, et cetera).

2.3 Crosspoints

2.3.1 *Main Characteristics*

The main characteristics of the crosspoints include the use of 3 sealed contacts per point, magnetic latching, and coordinate control with automatic release of previous connections. Of the 3 contacts, 2 are for the conversation and the third is for testing links, verification of established connections, and identification of one of the ends of the chain when starting from the other end.

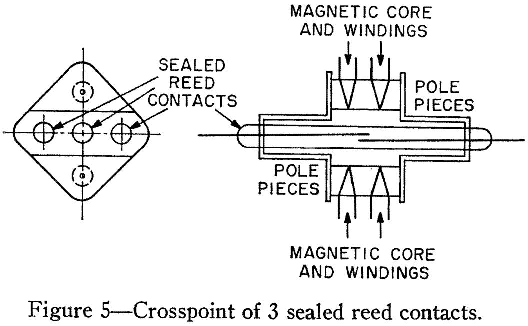

Figure 5—Crosspoint of 3 sealed reed contacts.

2.3.2 *Structure of the Crosspoint*

As shown in Figure 5 a crosspoint is made up of 3 sealed reed contacts, 2 magnetic cores, and 2 pole pieces. The soft-iron pole pieces guide the magnetic flux of the cores toward the contacts. The magnetic alloy cores are always magnetized, either in one direction or the other. Depending on the relative direction of magnetization of the two cores, 4 stable conditions of the crosspoint contacts can be obtained, as Figure 6 shows. Two of these conditions open the contacts and the other two close the contacts.

2.3.3 *Coordinate Control*

The principle of the coordinate control is shown in Figure 7. The two control cores, N and N',

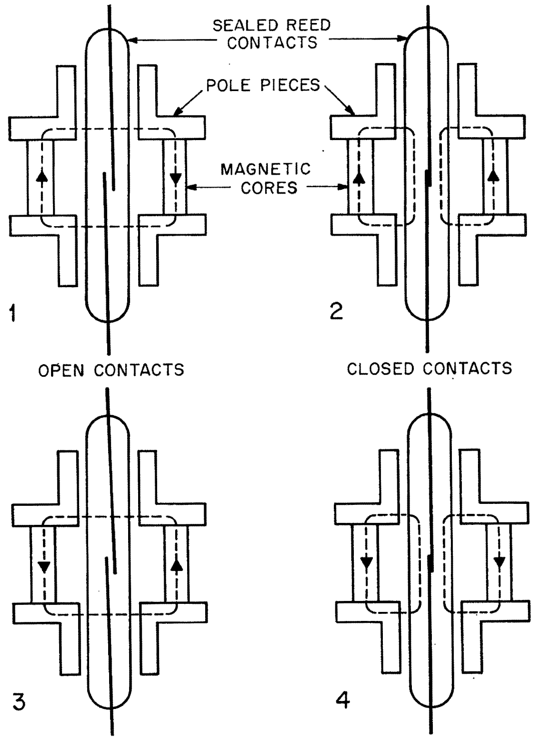

Figure 6—Of the 4 magnetic conditions shown, 2 open the reed contacts and 2 close them.

each carry two windings, X',Y and X,Y', that have the same number of turns. Operation is by simultaneous application of a pulse on each input of the pairs H,H' and V,V', corresponding, respectively, to the horizontal and to the vertical coordinates of the crosspoint to be controlled. It is necessary that the pulses be of unequal duration; twice as long, for example, on the H and V as on the H' and V' wires.

The role of these pulses is not only to act on the selected crosspoint but to release the operated crosspoints in the column and in the row involved.

For crosspoint *01* of Figure 7, for example, current through windings X and X' produce a magnetic field saturating the core with which they are associated. The direction of the windings is such that the two fields are in series. In consequence the two cores acquire or keep a magnetic flux linking one core to the other via the pole pieces. The sealed contacts open or remain open. This is case 3 of Figure 6.

For crosspoint *10* of Figure 7 and on all the crosspoints of the same vertical, except *00*, only the windings Y and Y' are energized and

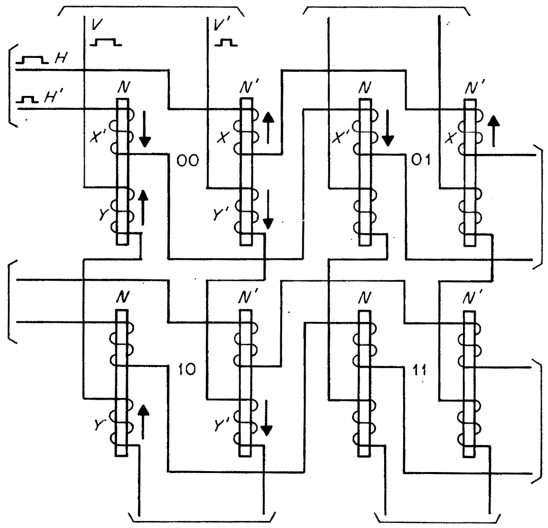

Figure 7—The pulses operating crosspoint *00* will open all other crosspoints in the vertical and horizontal coordinates of *00*.

the result is the same as before with the inverse direction of flux circulation; this is case 1 of Figure 6 and the crosspoints are open.

At the intersection of the vertical and horizontal coordinates for crosspoint *00*, the direction of the windings of each core is such that during the short pulse, the fields created annul each other and do not affect the contacts. The long pulses that persist after the short pulses terminate magnetize the cores in opposition via windings X and Y. The flux created by each core cannot return through the other and a part of this flux passes through the sealed contacts, which close. This is case 2 of Figure 6.

It is inherent in this system that the closing of a selected crosspoint results from currents that open all other crosspoints in the horizontal and vertical coordinates involved. Thus at the end of a communication the engaged crosspoints can be ignored as they will be automatically released on the establishment of following connections.

2.3.4 *Control Pulses*

About 650 ampere-turns are necessary for switching a magnetic core. A coil of 65 turns has been chosen, which requires a control current of 10 amperes. Despite this relatively strong current, the energy expended to operate a crosspoint is small, the control pulses being of short duration; about 1 millisecond for the long pulses, and 0.5 millisecond for the short pulses.

2.3.5 *Practical Construction*

The crosspoints are assembled in matrices of 10 by 10. Each matrix is assembled as a plug-in drawer, which can be seen in Figure 8.

The *H 50* miniature reed contact developed by Standard Elektrik Lorenz is used. The cores are an alloy of iron, cobalt, and vanadium. The coils are wound in sets of ten by an automatic machine without cutting the wire between them. These various subassemblies are shown in Figure 9.

2.4 Junctors and Multiregisters

2.4.1 *Role of Junctors*

As has been shown the switching network connects subscribers to the junctors, under multiregister control. In a conventional electromechanical system, junctors perform certain functions as follows.

(A) Feeding of microphone current to the calling or called subscribers' stations and sending of ringing alternating current toward the called subscriber.

(B) Supervising subscrbers' lines to detect if the handset is on-hook or off-hook.

(C) Interpreting supervisory signals to determine what switching is to be done in the junctor.

In a semielectronic system, the use of conventional relays for these functions would require too large a part of the exchange for the junctors, the network and electronic control being made up of miniature items. To avoid this, the volume of the junctors has been reduced in two ways.

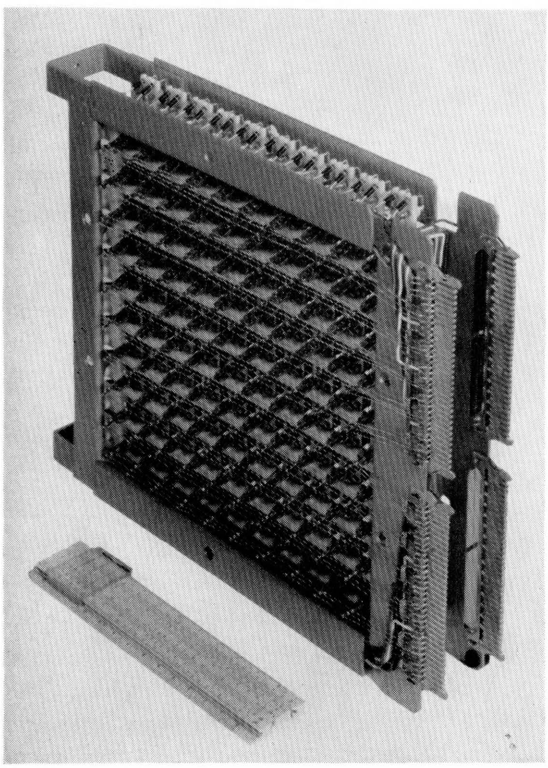

Figure 8—Plug-in drawer accommodating 100 crosspoints in a 10 by 10 array.

(A) All the logic operations, that is to say the interpretation of signals received by the junctor, have been placed in the central control unit.

(B) Use of miniature relays in the junctor. In Artemis, these relays use the same sealed reed contacts as the crosspoints.

This division of the tasks between the junctor and computer requires two distinct functions; the periodic test of the junctor by the computer carried out by an apparatus called a "scanner" and the sending of orders to close or open relay contacts from the computer to the junctor through an apparatus called a "distributor."

The distribution will be called slow if the apparatus that controls it receives the order from the computer, transmits it to the junctor, verifies that the corresponding relay has operated or released, and replies to the computer. The busy time of the distributor will be measured in milliseconds.

The distribution will be called rapid if under control of the computer the distributor activates an electronic flip-flop that will operate the junctor relay. The busy time of the distributor will then be measured in microseconds.

The rapid distributor is always used in special junctors, such as senders and receivers, in which the signals are short and must be operated on without delay.

2.4.2 *Test Points*

A number of test points are provided to each junctor to permit the multiregister to determine its condition. The greater number of these correspond to the condition of external lines, subscribers' lines, or trunks between exchanges. The apparatus connected to the line to detect the condition cannot be a reed relay that, having no possible adjustment, could release in the

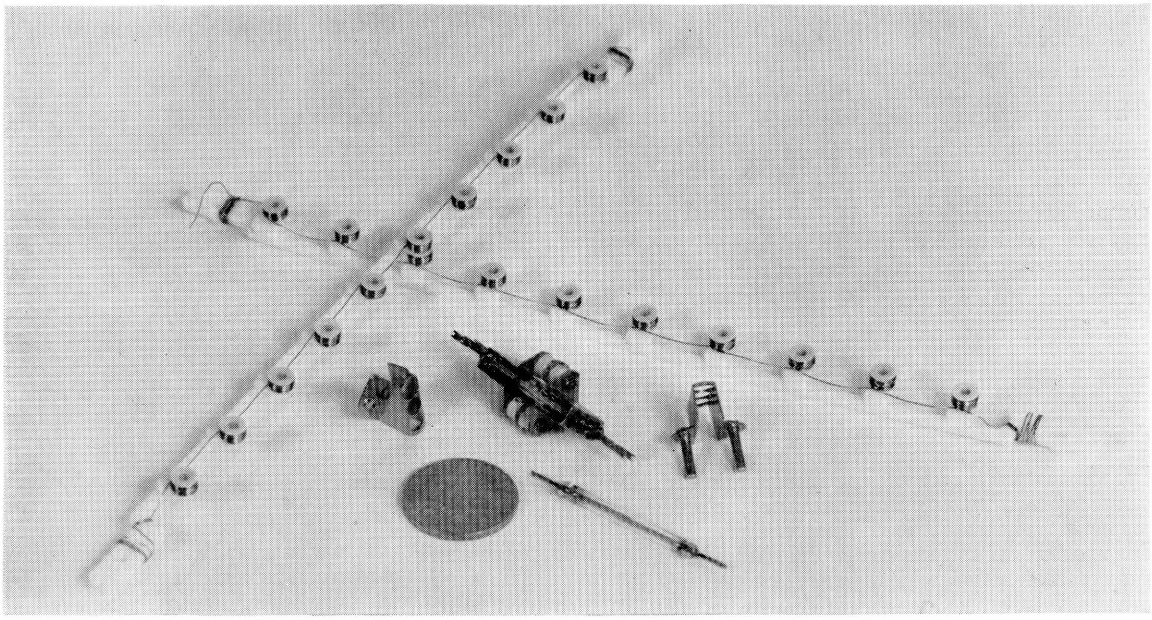

Figure 9—Subassemblies for the crosspoint matrices.

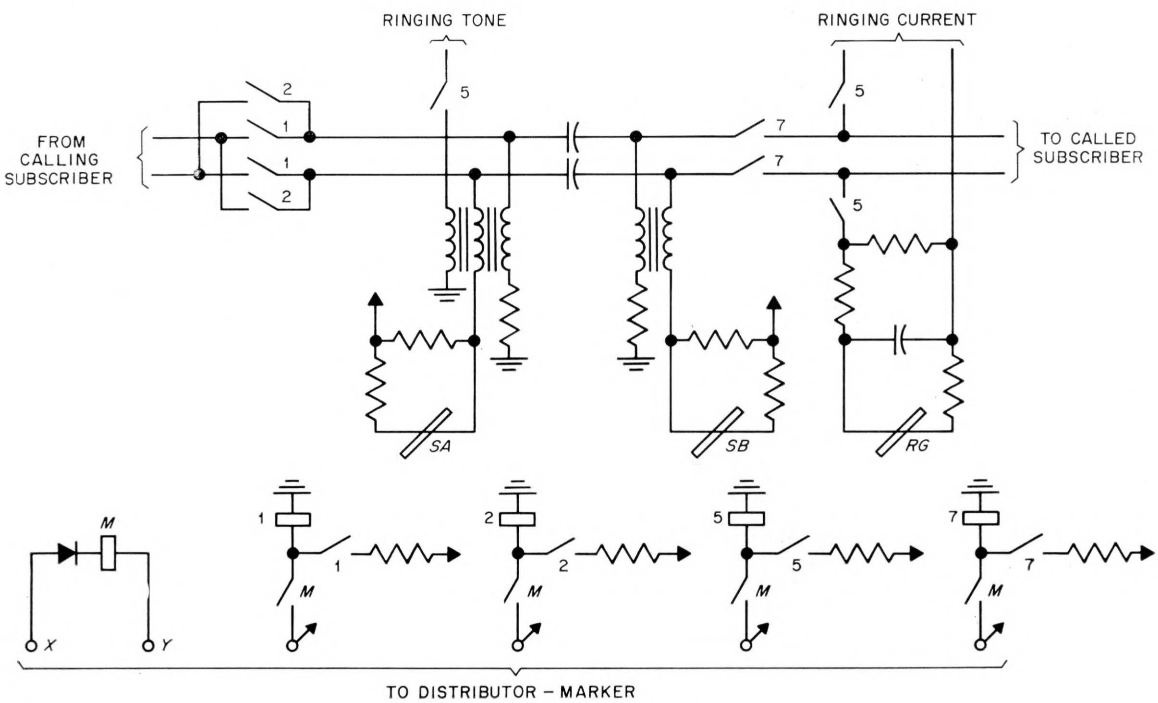

Figure 10—Principle of the local junctor.

presence of line leakages or because a high-resistance relay is connected to the line at a distant exchange.

The normal supervisory relays are replaced by transfluxors with 3 openings that are mounted in matrices. The winding in the large hole is connected into the line to be supervised. Each of the two small holes is allotted to a scanner connected to each multiregister, which allows testing of the same junctor by the two multiregisters independently of each other. Magnetic material with a rectangular magnetization characteristic permits detection of the marginal conditions that are tested for.

2.4.3 *Junctor Bay*

Figure 10 shows the principle of the local junctor. It is seen that 3 transfluxor test points *SA, SB,* and *RG,* have been used, 2 for the supervision of the subscribers and the third for the detection of the called subscriber hanging up in the ringing phase. Several relays assure switching of the line wires. The relay *M* allows the junctor to be connected to the control apparatus (distributor-marker), which controls the operation or release of the junctor relays.

The junctors are grouped by bays of 100 with plug-in circuits as shown in Figure 11. There are a large number of junctor types, but each can be plugged in at any place in the bay.

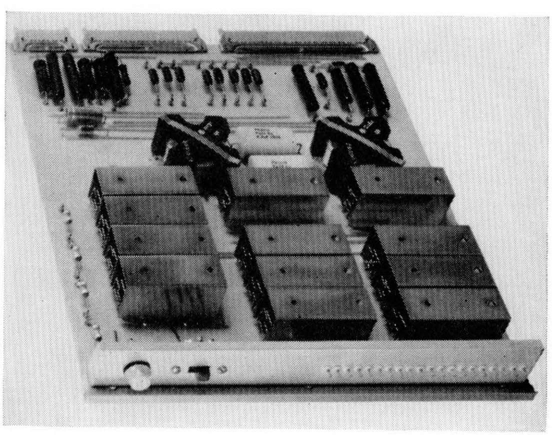

Figure 11—Local junctor.

2.5 Control of Switching Network

2.5.1 *Logic Devices*

It has been shown that a part of the logic functions are performed by electronic devices that are associated with the switching network. They receive orders from the multiregisters and perform the required operations. These operations, including the setting of crosspoints, are so rapid that, even for an exchange equipped to maximum capacity, a single such device is sufficient.

This device is called a control unit. For reliability two control units have been provided but, contrary to the case of the multiregisters, only one control unit is in service at a time. This implies that each control unit might be connected to one or the other of the multiregisters, as Figure 12 indicates.

A certain number of electronic devices that are directly connected to the crosspoints are not duplicated, for example the electronic gates devoted to the link availability test, and the controlled rectifiers serving to direct the control pulses toward the selected crosspoint. These devices form the markers in Figure 12. Each marker is associated with a group of crosspoint matrices which are called selection elements.

The selection elements are of two types. The terminal selector is for traffic concentration and serves 200 subscribers in two matrix stages of 20 by 10. The group selectors have 100 inputs and 100 outputs to handle heavy traffic and are in two matrix stages of 10 by 10.

The marker not being duplicated, the size of the selection elements has been made small so that a fault in a marker will not affect a large number of subscribers or junctors.

An intermediate distributing frame is provided between terminal selection elements and group selection elements. Any number of links may be between the group and terminal selectors. Mutual-aid links are provided between the different terminal selectors, allowing connections between subscribers and junctors to be established through 4 or 6 stages of crosspoints. The principles of route testing, described later, allow exchanges of large capacity to use two group selection elements in series.

The control unit can control the operation of the relays in the junctors under the direction of the multiregister, in the same way that it controls the operation of the crosspoints. Through a device associated with 100 junctors and called a "marker-distributor," it controls the function of slow distribution described above.

2.5.2 *Third Wire*

The 3rd contact of the crosspoints provides for a 3rd wire parallel with the speech wires and connecting the subscribers' line equipment to the junctor. This 3rd wire is connected to earth in the junctor, as Figure 13A shows.

This provides for operating the cutoff relay in the individual subscriber's equipment while still isolating the line from the device for detecting calls. The cutoff relay has 2 sealed contacts identical with those of the crosspoints that are held closely by a permanent magnet when the relay is at rest and are held electrically when operated.

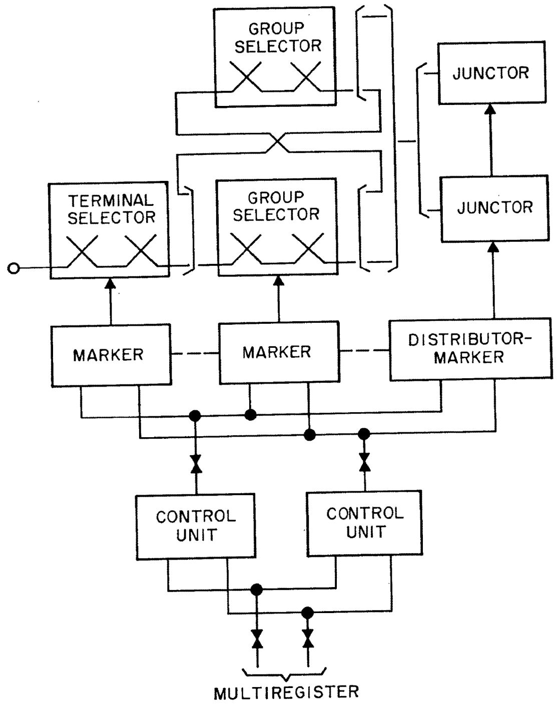

Figure 12—Network structure.

The 3rd wire also provides for testing links in all stages of the chain. A link will be considered busy if its 3rd wire c is to earth. At the end of communication the interruption of earth potential over wire c in the junctor acts throughout the whole chain and all links become free for other calls. The engaged crosspoints will be released automatically by following calls. The gate serving as a link availability test is shown in Figure 13A in the 2nd matrix stage.

The possibility of testing the condition of the c wires at any stage whatever is used for the selection of a path through the network, as will be described in Section 2.5.3, and moreover allows busy test of a wanted subscriber, identification of a subscriber connected to a given junctor and of the links making up the connection, and the treatment of faulty calls.

Test of a wanted subscriber. The test to determine if a wanted line is free is made by verification of the potential on wire c in the same way as for the test of an intermediate link.

Identification of a subscriber. The identification of a subscriber starts from a junctor by testing the availability of the 10 input links of the matrix to which the junctor is connected. A second test of these links after disconnecting the earth indicating the busy condition is then made. If in the 1st test there were n free links among the 10, there will be $n + 1$ in the 2nd test. The freed link forms part of the connection to be identified. Knowing this link, the last-but-one matrix is known and the identification of all the links and finally of the subscriber are determined in this manner. The link availability tests being rapid, the interruptions of earth potential on the c wire of the junctor can be short enough to avoid the release of the cutoff relay in the subscriber line circuit.

Faulty connections. In the case of a faulty connection each subscriber is connected across the network to a local junctor or to any outgoing junctor whatver. This junctor is put in a "trouble condition" in which the busy earth of the *c* wire can be controlled in the central control unit. On establishment of a normal connection, if the network is overloaded, the busy earth on the junctors in a faulty connection is disconnected throughout. If this permits a free path to be found, the junctor involved in the faulty connection is identified by interrupting the earths on wires *c* individually. Then as indicated above, the subscriber who blocked the routing of the call is identified, the chain involved is freed, the connection that was sought to be made is established, and the subscriber involved in the fault is reconnected if possible to another junctor. The rearrangement of the network thus carried out does not require increasing the cost of the subscriber's individual equipment.

2.5.3 *Link Selection*

Although it is possible to test all links of the network for availability, the number of routes connecting an input *A* to an output *B* may be greater than 1, so knowledge of the addresses *A* and *B* is not sufficient to determine in a simple manner the links that it is necessary to test. The first operation, knowing *A,* will be to mark all available links coming from *A*. This is done by associating with the wire *c* and with the link-availability gates, shown in Figure 13A, a marking wire *d,* parallel to wire *c* and forming what may be called the replica network. Figure 13B shows the paralleling of wires *c* and *d*. The marking signal coming from *A* (positive potential) is propagated through the network if there is no short-circuit by the busy *c* wires: it is regenerated at each stage by an amplifier associated with each matrix. When mutual aid has been provided at a selection stage the amplifiers introduce a delay in the propagation of the marking signal, which allows the direct paths to be recognized from those using the mutual-aid paths.

If at least one available path connects *A* and *B,* the marking signal reaches the last matrix. The choice can then be made of one of the input links of this last matrix by short-circuiting all the corresponding wires *d,* other than the first, then all others than the 2nd, et cetera, by means of the diodes *DC* (Figure 13C). Thus a list of which of the 10 links is useable is obtained and one is chosen. The knowledge of the input to the last matrix gives the number of the last-but-one matrix, the crosspoints being operated inside the group selection element, and the choice of an input proceeds as above.

Now, it is necessary to know the terminal selection element in the normal case, or the group element if there is mutual aid, connected to this chosen entry, and the number of the matrix in this element. For this, the wire *d* (Figure 13D) is used. After suppression of marking on *A,* a positive signal called a "chain backward signal" is sent back, which, received in the preceding selection element, allows this element to be identified either by the chosen matrix or by diodes *DM', DS', D,* shown in the drawing.

2.6 Reliability and Maintenance

Reliability and facilities for emergency repairs have been considered at all stages of the Artemis project. The crosspoints and the junctor relays use very reliable sealed contacts that require neither maintenance nor adjustment. The electronic components are all proved components. The circuits have been designed to provide a large operating margin. Besides, all the subassemblies (crosspoint matrices, junctors, electronic circuits) are mounted on plug-in connectors for rapid replacement in case of trouble.

2.6.1 *Control Unit Reliability*

The control unit of the network fulfills in an autonomous way a certain number of important telephone functions; detection and identification of subscribers' calls, connections, orders to the junctor relays, and identification of the paths established through the network. These different operations are subject to numerous controls, allowing any abnormal operation to be detected. Thus each connection in the network is followed by a control for identification of the established path. It is thus verified that the required connection, and it alone, has been established. In the same way every order to a junctor is followed by a test of a contact of each relay actuated. In many of these controls, each elementary operation is controlled by a delay circuit and by code checkers (rendered simple by the systematic use of 1-out-of-n or 2-out-of-n codes).

Any anomaly in the operation of a control unit is signalled to the multiregister. The latter holds a record of faults and can either simply start an alarm or decide in case of multiple faults on the

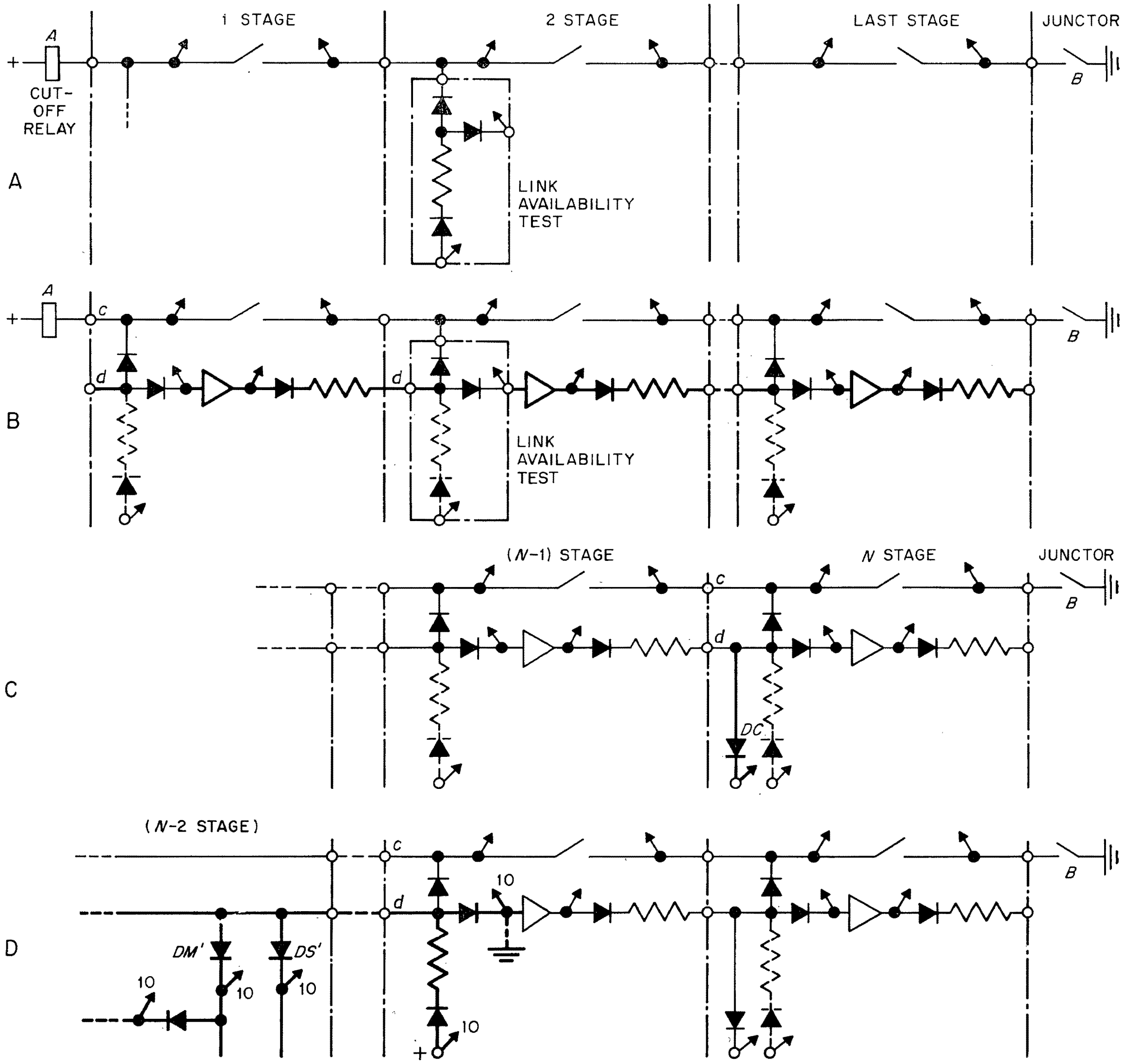

Figure 13—Use of the 3rd wire.

withdrawal from service of the control unit concerned.

2.6.2 *Multiregister Reliability*

In the multiregister, the memory data and the programmed instructions are systematically accompanied by redundant bits, controlled at each transfer. Another control is furnished by the delay circuits, easy to put into operation, due to the cyclic operation of the program (cycles of 10 and of 200 milliseconds). These controls, completely wired, are sufficient to detect the great majority of operation anomalies. However, in addition, there are some programs of routine tests verifying the satisfactory operation of the test instructions and, in a more general way, all the circuits wherein a disturbance might not be detected by the wired controls.

2.6.3 *Correction Programs*

When one of the control systems detects a fault, the multiregister interrupts the program, stores the fault, and makes a jump to a correction program, chosen on the nature of the detected fault. This program tries by several simple operations to set back the multiregister. For example, if there is a fault of parity in a register, the program wipes out this register by dropping the call with which it has been engaged, and restarts operation at that previous point. In more-serious cases, the register can be made to drop the set of calls under treatment in this multiregister (communication being established or released). In this case it wipes out all the temporary memory and starts it up again from the data in the magnetic drum (see Section 2.2.1). Finally, the correction program puts the multiregister back in normal service and the interruption of service has lasted only several seconds.

It may be remarked that the automatic setting back of the multiregister that has just been mentioned allows a restart only in certain cases as for parasitic faults of short duration or for program loops resulting from rare unforeseen configurations. If a real fault occurs in a component, setting back the multiregister will not cure the fault or the program will loop back on itself. In these two cases it will be necessary to await the intervention of maintenance personnel.

We must not overlook among the correction programs the systematic tests that the multiregister carries out at low priority. These tests include the control unit, explorer-distributor, junctors, and subscribers' lines. Anomalies found are identified by the multiregister to furnish to maintenance an indication of the defective devices to be withdrawn from service.

2.6.4 *Diagnostic Program*

When a faulty multiregister stops and the correction programs are unable to make it restart, intervention of maintenance personnel is necessary. The multiregister is then isolated from the network and diagnostic programs are carried out. The temporary memory and the drum are tested by special programs verifying that their operation is in accordance with specifications. Any fault at this level is then easily localized. To verify the internal logic of the multiregister is more delicate. It was decided, in Artemis, not to design a complete set of programs permitting automatic fault localization. Attention has been directed rather towards a semiautomatic procedure having greater flexibility. The maintenance personnel have at their disposal a variety of small simple programs, which carried out one after the other according to a predetermined procedure, will indicate the faulty device. This procedure is much more practical than providing a very complicated program for automatic diagnosis since a human operator must inevitably replace the defective device.

3. Conclusion

The Artemis automatic exchange, shown in Figure 14, was installed at the Boulogne plant of Le Matériel Téléphonique in 1966. It represents the advances reached in the studies on electronic switching carried out for several years by Le Matériel Téléphonique and sponsored by Socotel. This installation has provided actual experience not only with the hardware but also with the software, the programs to permit operation both as a private automatic branch exchange and as a part of the public telephone network through its integration into the Paris telephone network as a trial Paris exchange. The methods to interconnect Artemis with the different types of exchanges existing in Paris are extremely simple and general. Only the program of the multiregister is concerned with the specific problems of interconnection. The special junctors needed for any new case are generally very simple and can be plugged in at any convenient place in the standard junctor framework, which makes it very easy to revise and extend the facilities.

Artemis was also used to test the effectiveness of duplicating multiregisters. The system chosen was based on a division of traffic and this raised a number of problems that could best be solved by experimentation. Also it was possible to resolve the problem of reliability with centralized control by the use of either special circuits or special programs depending on the particular situation.

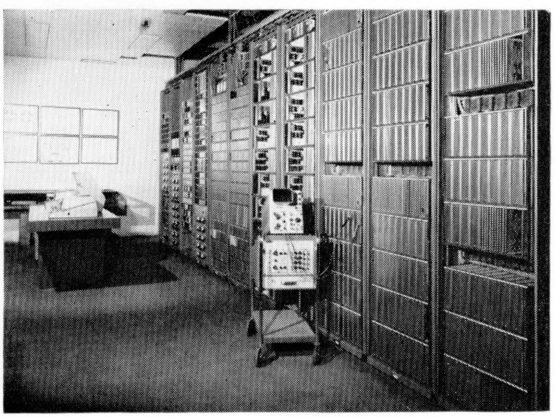

Figure 14—General view of the Artemis exchange.

Artemis does not however represent completion of the studies of Socotel in the field of space switching with sealed reed contacts. Some improvements are already apparently desirable and can be introduced later.

(A) Grade the subscriber stages to decrease the number of crosspoints.

(B) Increase the size of the selection elements as improvement in component reliability permits.

(C) Introduce integrated circuits to decrease cost and volume and to increase reliability.

(D) Adapt the multiregisters to improvements in computers, mainly to facilitate operation speed and memory technology.

To conclude, it can be said that experience has proved that the principles chosen are viable and hold promise of being adaptable to the evolution of electronic switching in the public telephone network.

Jean Duquesne was born on 14 February 1932, at Rennes, France. He received a degree of Engineer from the Polytechnic School of Paris in 1954 and a degree of Telecommunication Engineer in 1957.

In 1957, he joined the Centre National d'Études des Télécommunications (C.N.E.T.), the research laboratory of the French Telecommunications Administration, as a telecommunications engineer.

Since then he has participated in the studies of the Recherche sur les Machines Électroniques (R.M.E.) at Issy-les-Moulineaux.

He was concerned chiefly with the design of electronic switching for the first two electronic telephone exchanges in Europe that employ stored programs (Socrate and Aristote) which have been in experimental operation at Lannion since 1964.

Mr. Duquesne is a member of the Société Française des Électroniciens et des Radio-Électriciens and of the Institute of Electrical and Electronics Engineers.

Guy Jean Le Strat was born at Lanester, France, in 1934. In 1959, he received a degree of Civil Engineer for Telecommunications.

He entered the Switching Research Department of Le Matériel Téléphonique in 1962, where he worked on computer assistance to Pentaconta engineering. In 1964, he undertook the programming of the Artemis quasi-electronic telephone exchange.

Albert Regnier was born on 2 November 1930 at Cherbourg, France. In 1952, he received a degree of Engineer from the Polytechnic School of Paris and in 1955 a degree of Civil Engineer for Telecommunications.

He joined Le Matériel Téléphonique in 1955 and designed switching circuits for rotary and Pentaconta systems. Since 1960, he has been a member of the Switching Research Department, where he is in charge of electronic switching developments, mainly of the Artemis project.

Spagnoletti Appointed President of Manufacturers Association

P. H. Spagnoletti, Director of Business Development of Standard Telephones and Cables, has been appointed president of the Committee of European Association of Manufacturers of Active Electronic Components (CEMAC). This organization was formed in January 1967 to promote compatibility of specifications, organization, and procedures for active electronic components throughout Europe. Its aim is to arrive at specifications that will be recognized throughout Europe and, through the International Electrotechnical Commission, develop into world standards.

Awards Program Instituted by International Telephone and Telegraph Corporation

Under an Awards Program instituted in 1966 by the International Telephone and Telegraph Corporation, it will honor 29 employees in 10 affiliated companies with cash awards totaling $58 000 for their development of inventions, new products, and new services. Commemorative medallions and certificates will accompany the awards and their companies will receive trophies suitable for display.

In the category of products and services, two joint first awards were granted.

J. P. Van Etten and C. J. Pasquier of ITT Federal Laboratories (United States of America) share $10 000 for development of Loran-C air navigation equipment now being implemented on a worldwide basis.

W. Kloepfer and G. Sidow of Standard Elektrik Lorenz (Germany) share $10 000 for development of military mobile radio sets being produced and used in several Western European countries.

Four other awards were made in this category.

T. N. Tilman and H. W. Walker of ITT Jennings (United States of America) share $5000 for development of vacuum coaxial relays for remote switching of high-power radio circuits.

R. J. M. Andrews, W. J. Archibald, B. M. Dawidziuk, B. D. Mills, A. H. Roche, and J. F. Tilly of Standard Telephones and Cables (England) share $5000 for development of a 160-circuit submarine-cable telephone repeater for deep-water long-haul service.

W. Heinke, H. Keller, L. Micic, and H. Pfander of ITT Semiconductors Europe (Germany) share $5000 for development of a special semiconductor diode for tuning ultra-high-frequency television receivers.

G. De Bruyne, A. Peeters, E. J. H. De Raedt, R. Ruelens, S. Simon, and F. Verstuyft of Bell Telephone Manufacturing Company (Belgium) share $5000 for development of a rotary telephone system with solid-state components providing all services required in a modern exchange.

In the category of inventions, two joint first awards were granted for the combining of speech and data in a single transmission channel, the data being transmitted during idle periods in the speech.

F. T. Cassidy, Jr., of ITT World Communications (United States of America) shares $10 000 for his invention of a Channel Combiner and Divider for Automatic Alternative Voice and Data with E. P. G. Wright of Standard Telecommunication Laboratories (England) for his invention of Interpolated Data and Speech Transmission.

Four other awards for inventions include the following.

R. A. Felsenheld of ITT Federal Laboratories (United States of America) receives $2000 for a tunable broadband antenna of small dimensions for transmitting over a wide range of frequencies.

H. F. Sterling and R. W. Warren of Standard Telecommunication Laboratories (England) share $2000 for a method of processing extremely pure materials having very-high melting points.

E. S. Guttmann of ITT Gilfillan (United States of America) receives $2000 for an airborne navigation display system.

J. P. Le Corre of Laboratoire Central de Télécommunications (France) receives $2000 for a telephone switching system having facilities for handling heavy traffic with increased efficiency.

Microminiature High-Frequency Transmitter-Receiver

J. LISIMAQUE
J. RIBOUR
Le Matériel Téléphonique; Paris, France

1. Introduction

The application of single-sideband modulation to mobile and portable equipment appeared only after the introduction of semiconductors.

It was introduced with simplified sets having preset frequencies in which the stability of the carrier derived from an ordinary quartz crystal oscillator was insufficient and the frequency had to be corrected by special means.

This solution was acceptable for communication between two mobile stations but was completely inadequate for intercommunication among a large number of mobile stations as the simultaneous adjustment of frequencies leads to almost insurmountable difficulties in network operation.

A satisfactory solution stemmed from the development of very-stable quartz oscillators with satisfactory ageing properties and small dimensions. Such an oscillator controls a synthesizer, which supplies from a reference frequency all the possible channels in the range spaced by the selected increment. However, these synthesizers are generally highly complex as well as cumbersome and heavy when good performance is required.

Microelectronics offers new possibilities. In particular, the use of integrated circuits and digital techniques permits reductions in both dimensions and weight. Power consumption is still a problem but is of lesser importance in mobile equipment than in portable equipment.

2. Features of the *LMT 3527 A* Equipment

The *LMT 3527 A* airborne equipment to be described consists of the following components shown in Figure 1.

(A) Exciter-receiver including the receiver circuits, frequency generator, and transmitter circuits up to 7 watts.

(B) High-frequency power amplifier of 100 to 400 watts, according to requirements.

(C) Antenna coupler.

(D) Control unit.

The characteristics of the exciter-receiver, which is common to several versions, are listed below. The other parts of the equipment, such as the amplifier and the antenna coupler, use conventional techniques and will not be discussed. The control desk will be described together with the principle for remote control.

2.1 Exciter-Receiver

2.1.1 *General Characteristics*

Dimensions: 340 by 198 by 124 millimeters (13.4 by 7.8 by 4.88 inches). This is the 1/2 *ATR* cabinet.

Weight: Approximately 6 kilograms (13 pounds).

Frequency range: 2 to 29.999 megahertz.

Number of channels: 28 000 (every kilohertz).

Power supply: 28 volts direct current.

Power required: 5.5 watts for reception and 25 watts for 2-signal transmission.

Modulation: Single (upper) sideband and double sideband with carrier.

Figure 1—*LMT 3527 A* airborne transmitter-receiver for operation from 2 to 30 megahertz.

Frequency stability: Maximum error of 4 hertz throughout the range.

Band pass for modulation: 400 to 3000 hertz.

2.1.2 *Transmission*

Output power exciter: 7 watts without amplifier and 100 to 400 watts with amplifier.

Intermodulation distortion: 35 decibels.

Carrier-wave attenuation: 40 decibels.

Audio-frequency compression: 15 decibels.

2.1.3 *Reception*

Sensitivity: 0.5 microvolt gives a $(S+N)/N$ ratio of 10 decibels.

Gain control: 6-decibel variation in audio-frequency level results from a variation in radio-frequency input level between 5 and 100 000 microvolts.

Image rejection: 65 decibels.

Intermediate-frequency rejection: 80 decibels.

Audio-frequency output level: 200 milliwatts.

2.1.4 *Mechanical and Climatic Characteristics*

Vibration: Withstands 2.5 g (gravity units) from 20 to 500 hertz.

Temperature range: From −40 to +70 degrees Celsius in service.

Altitude: With natural cooling up to 10 000 meters (33 000 feet) in service.

2.1.5 *Remote Control*

Frequency setting is by means of sequential information over 2 wires between the control unit and the exciter-receiver and over 7 wires from the exciter-receiver to the other subunits. A magnetic memory in the control unit provides for 10 preset frequencies.

3. General Principles

The dimensions of the exciter-receiver could not be kept within 7 liters (425 cubic inches) using miniaturization techniques with conventional components and analog circuits. The conventional components could have been shrunk in size through the use of specially designed hybrid circuits either in thin or thick films, but this solution was not selected because the large number of different types of circuits involved would require a heavy investment. The difficulty of producing high-quality inductances within small dimensions and the accuracy required from components in analog circuits also made this solution unattractive.

The guiding principles included (A) adopt digital solutions wherever possible, (B) use conventional commercially available integrated circuits, and (C) tolerate no sacrifice in electrical performance.

3.1 Digital Techniques and Microminiature Circuits

3.1.1 *Adjustable-Divider Synthesizer*

Methods of pure synthesis successfully applied to laboratory equipment cannot be used in a lightweight unit of small dimensions since the required filtering circuits are necessarily cumbersome if they are to be efficient.

The principle of a synthesizer is given by

$$\frac{F_0}{A_0} = \frac{F}{A} \quad \text{or} \quad F = F_0 \frac{A}{A_0}$$

where

F = frequency at output of synthesizer
F_0 = frequency of reference oscillator
f_0 = frequency increment or frequency selection step
A = F/f_0
A_0 = F_0/f_0.

To effect this arithmetical combination, an oscillator signal is applied to a frequency divider having an adjustable dividing factor A. The signal obtained is compared in phase with a pilot signal from the reference signal F_0 through division by a fixed ratio A_0. This comparison gives an error signal that corrects the controlled oscillator so that the condition $F/A = F_0/A_0$ is fulfilled. Frequency division is effected by counting pulses using only integrated circuits for this.

3.1.2 *Automatic Digital Tuning*

In equipment of this type, the input circuits of the receiver and the local oscillator must be tuned to a desired frequency within a large range. The mechanical adjustment of reactors does not lend itself to miniaturization and the accuracy required in their manufacture increases the cost of the equipment.

Varactor diodes, which act as voltage-controlled capacitors, are used to tune the receiver input and local-oscillator circuits. The control voltages are adjusted in suitable steps, the required step values being stored in binary notation.

3.1.3 *Remote Control*

The remote setting of the operating frequency from a control unit requires transmission of logic information consisting of a certain number of bits. For equipment with 28 000 possible channels, this number is equal to 43 if a bit is made to correspond to each digit in each decade; it is equal to 25 if the Arinc "2 out of 5" code is used.

Parallel transmission of this information over 25 wires requires much more weight than can be justified for miniature equipment in aircraft. Therefore this information is transmitted over 2 wires in a 17-bit sequential mode: 4 bits each for the 1-, 10-, and 100-kilohertz decades and 5 bits for the 28 steps of 1-megahertz each. The same 2 wires can also transmit the equivalent information recorded in a nondestructive magnetic memory corresponding to each of the 10 preset frequencies. All coding and decoding operations are performed in integrated circuits.

3.2 Miniature Circuits for Other Functions

Apart from the use of integrated circuits for digital functions, microminiaturization can be easily introduced for such functions as operational amplifiers, digital-to-analog converters, differential amplifiers used in stabilized power supplies, thermostat system for the quartz oven, and even in broad-band amplifiers associated, for example, with additional quartz filters.

Switching operations, which are numerous in equipment covering such a very large frequency range, can be effected electronically. Thus, it is possible to put the crystal filter associated with each frequency synthesizer subrange into service simply by applying power to the output amplifiers and by means of logic gates at the input of filters.

Narrow-band filters are of ladder type and are equipped with subminiature crystals.

3.3 Limitations of Miniaturization

The transmission line and antenna matching stages are not readily reduced greatly in size.

Also, the switching of receiver frequency ranges often cannot be done electronically as such switches usually have very short linearity ranges and may also produce high-level parasitic signals at frequencies close to the useful signal that would produce undesirable signals through cross modulation in the receiver pass band.

Finally, it is necessary to mention the relatively large dimensions of decoupling circuits in all the power supplies and the circuits for protection against interference from radiation and conduction.

4. General Layout of the Exciter-Receiver

4.1 Operating Circuits

Two intermediate frequencies have been selected: 1 megahertz and 5 megahertz.

The amplifier for 1 megahertz uses a crystal filter that passes the sideband and suppresses the carrier.

For double-sideband telephone communication, the crystal filter is replaced by an inductance-capacitance filter with a pass band of about 6 kilohertz.

The 1-megahertz intermediate frequency is used throughout the range from 2 to 6 megahertz. The 5-megahertz intermediate frequency is used above 6 megahertz to improve the rejection of the image frequency up to 30 megahertz.

The circuits used are shown on the right side of Figure 2 for transmission and on the left side for reception. The first intermediate-frequency circuits and the sideband filters and amplifier are common to transmission and reception. Electronic switches can be used on these filtered signals.

The input signal to the receiver passes through 2 coupled circuits followed by a tuned amplifier stage. The input stage, which uses field-effect transistors, has a low noise level and is well protected against cross modulation. The circuits are automatically tuned after each change of the frequency controls. The receiver input circuits are also used in the transmitter chain to filter the signals after modulation. Here, the switching is by electromechanical means.

The broad-band transmitter amplifier delivers a 7-watt peak signal into 50 ohms. These signals have little intermodulation distortion but contain high-frequency harmonics that must be filtered at the input of the power amplifier. It is better to have the filtering circuits in the exciter than in the power amplifier.

The frequency synthesizer, shown in Figure 3, must supply a number of frequencies.

(A) 1-megahertz and 4-megahertz signals are used in the translation of frequencies in both the transmitter and receiver circuits.

(B) Pilot signals must be available in two ranges as a function of the frequency setting. The ranges are approximately 11 to 35 megahertz and 3 to 7 megahertz.

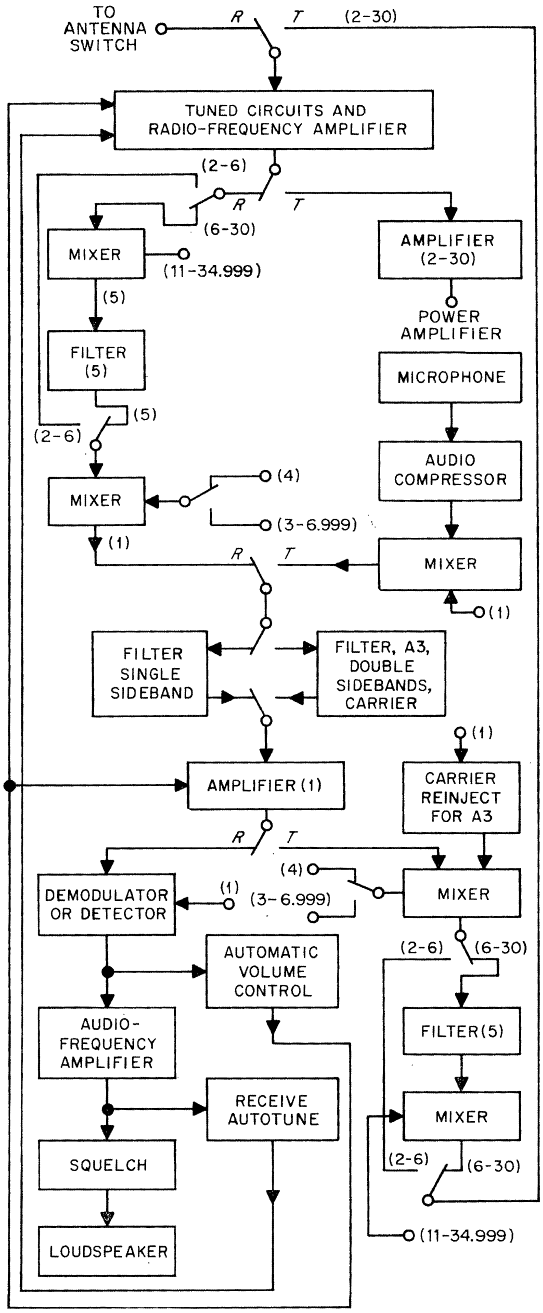

Figure 2—Transmitter-receiver diagram. Approximate frequencies are given in megahertz in parentheses. *R* indicates receive and *T* indicates transmit positions of switches.

The lowest range of the synthesizer (3 to 7 megahertz) is obtained by translation of the oscillator signal in the 31- to 35-megahertz range with a 28-megahertz signal derived from the 4-megahertz reference oscillator.

The 11-to-35-megahertz frequencies are actually supplied by six oscillators, each covering a subrange of 4 megahertz. They are switched by their power supplies.

The reference oscillator frequency of 4 megahertz is reduced to 10 kilohertz by the three dividers providing a 400:1 ratio. This is one input to a phase-control network. The output of the active controlled oscillator producing the range from 11 to 35 megahertz goes to a mixer that receives a suitable frequency from the 1-kilohertz interpolation chain and by selecting the proper division factor in the adjustable frequency divider, a 10-kilohertz signal is obtained to compare with that from the reference oscillator. Any drift of the controlled oscillator will produce an error signal that will retune the controlled oscillator.

4.2 Frequency Generator

In the synthesizer, the phase comparison is made at 10 kilohertz despite the fact that the setting increment is 1 kilohertz. A phase control loop operating at the interpolation frequency of 1 kilohertz with a corresponding sampling period equal to 1 millisecond would, by its very nature, be insensitive to very rapid drifts in the oscillator frequency.

The open loop gain must be limited to fulfill the stability criterion of the servo control, since, for a phase margin of 30 degrees, Bode's second law limits the slope of the relative variations in the gain-frequency curve to 5/3. The 10-kilohertz choice permits an increase in the gain at the origin of the open loop of 33 decibels.

Setting of the kilohertz decade is by interpolation using a quartz oscillator without special stabilization but in which the frequency and, consequently, the absolute error are divided by 128, thereby reducing the error introduced by interpolation to less than 1 hertz under all the operational conditions mentioned in Section 2.1.4.

The parasitic products resulting from this interpolation, which occur within the loop, are practically eliminated by the phase control.

4.2.1 *Electronic Tuning of the Receiver*

Electronic tuning avoids heavy electromechanical components. Furthermore, the receiver circuits are automatically tuned and do not require correction for thermal drifts.

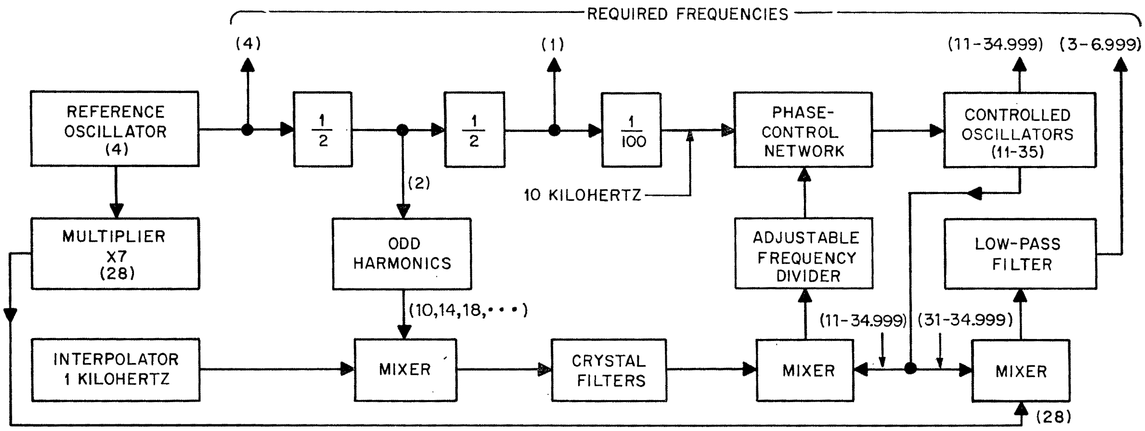

Figure 3—Frequency generator with frequencies in megahertz in parentheses.

4.2.2 *Redundancy*

The use of power-supply switching encourages the use of independent modules for similar circuits. Thus, a fault in one of the ranges does not result in complete outage of the equipment.

5. Specially Designed Circuits

5.1 Adjustable-Ratio Divider

Frequency division by a controllable number A is done by counting the number of periods in the input signal in groups of A and in producing a single pulse at the end of each group. For counting, the input signal is transformed into a square waveform.

Each rising edge of a square wave steps a binary counter. A coincidence system resets the counter to zero when the number of pulses corresponds to the dividing number A, which is applied in binary form to the divider by the frequency-setting device. As the dividing number may be in the hundreds, the divider includes a main counter with its coincident and zero-resetting system and a programming device to permit counting the number of pulses in several operations. Each step of the program corresponds to the units, tens, and hundreds of the number A.

Figure 4 shows the signals at the divider input, at the main counter input, at the programmer input, and at the divider output for division by 118.

5.2 Adjustment of Oscillator Frequency

For each frequency setting, the output voltage of the phase comparator is applied across a resistance voltage divider the attenuation of which varies step by step according to the state of a binary counter. See Figure 5.

The sets of pulses to be compared are applied to flip-flops B7 and B8; flip-flop B7 on the diagram receives one of the signals at its symmetrical input and the other at its reset-to-zero input. Flip-flop B8 receives the same signals but with reversed operate and reset connections. In this manner, the two logic states 01 and 10 are possible only if the signals are exactly interpolated as shown in Figure 6A. A third state 11 appears when several pulses of one of the signals are interposed between two pulses of the other as in Figure 6B, that is, when the repetition frequencies of the signals are not equal.

Detection of this third condition in a NOR gate steps the binary counter, thus changing the voltage across the varactor and the frequency of the controlled oscillator until it operates the phase control.

5.3 Automatic Tuning of Receiver

The input circuits of the receiver (Figure 2) are tuned by the biasing (between 10 and 100 volts) of varactor diodes having high reverse breakdown voltages. After changing the setting, or when switched on, a signal supplied by the synthesizer, after several mixing operations, is fed to the receiver input.

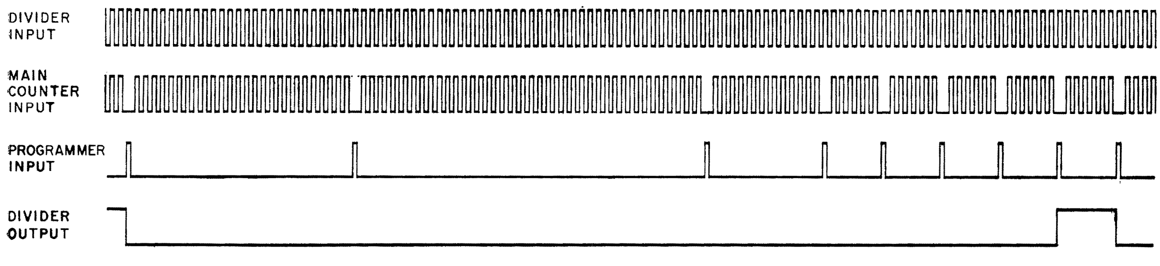

Figure 4—Waveforms in the adjustable divider.

This signal is at the nominal tuning frequency and has a fixed level. The polarization applied to the varactor diodes then decreases in steps from 100 volts down to 10 volts, according to the state of a binary counter controlling a digital-to-analog converter. The signal level at the output of the receiver thus varies step by step in accordance with the response of the filter in the intermediate-frequency system as shown in Figure 7. The stepping of the varactor voltage is stopped when the maximum level is attained, which voltage is recorded in the memory of the tuning counter.

As shown in Figure 7 the phase of the signal at the output of the low-frequency amplifier is compared with the phase of the binary-counter drive signal. The selectivity curve is, therefore, scanned in the manner shown, where it will be seen that the binary signals are subjected to a phase reversal immediately after the maximum value at resonance. This phase reversal is detected by digital circuits, which stop the counter.

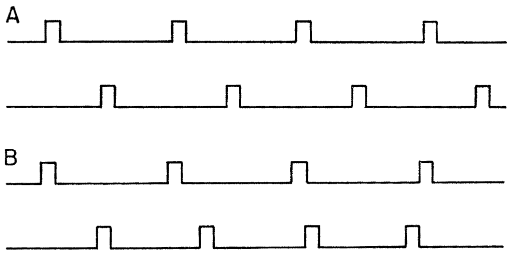

Figure 6—The pulses in the two series at *A* alternate. If as at *B* two pulses in the lower series are interpolated between two adjacent pulses in the upper series, the binary counter is stepped to change the frequency of the controlled oscillator.

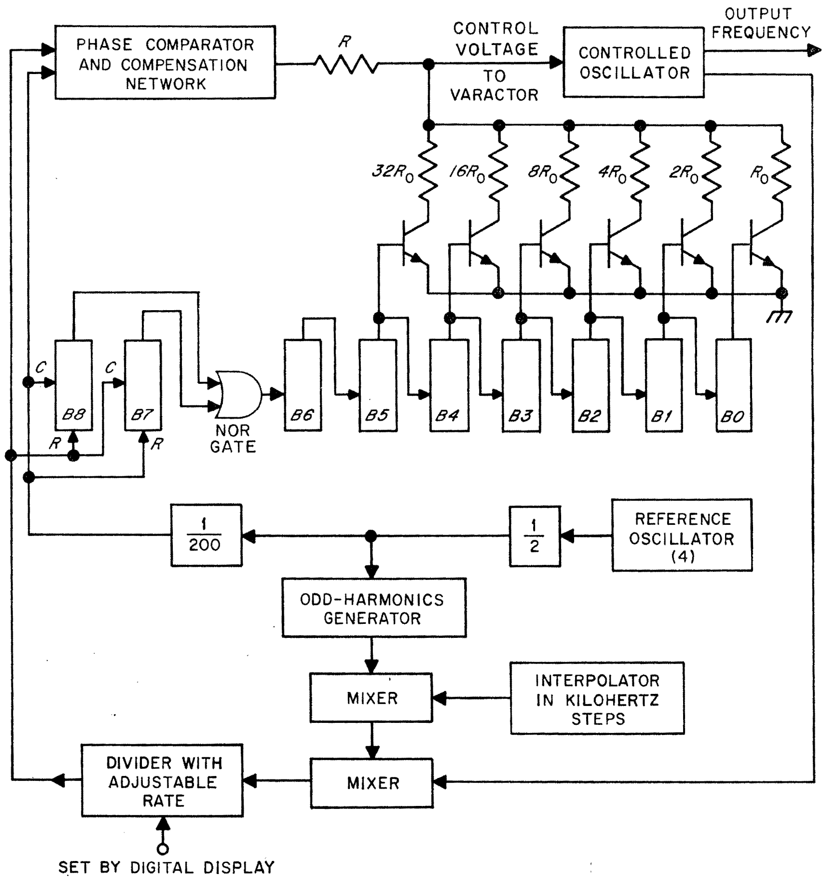

Figure 5—Method of adjusting the controlled oscillator.

6. Construction and Technology

6.1 Modular Construction

The exciter-receiver can be split into 9 units of various dimensions, which are plugged into a common chassis. Each of the units can be split into plug-in printed circuits or modules. This arrangement, shown in Figure 8, provides for two stages of maintenance, thus simplifying identification and replacement of defective components.

Of the 9 units, 3 make up the synthesizer and one each are for the transmitter, intermediate-frequency chain, receiver, power supply, range switching, and the quartz filter.

6.2 Modules

A standard size of circuit board measuring 82 by 50 millimeters (3.2 by 2 inches) is used for both the integrated circuits and the other components. Only the height above the board varies to accommodate the particular components but is required to be a multiple of 4.5 millimeters (0.18 inch). The circuits are printed on both sides with metallized holes for through connections. Sample boards are shown in Figure 9.

The plugs and sockets of the subminiature connectors require less than 25 percent of the available surface area of these very small boards.

The integrated circuits for fast logic (adjustable-ratio divider) are of the emitter-coupled-logic (ECL) technology. The remainder are low-consumption diode-transistor logic (DTL) with good noise immunity. Only components of military type already available on the market are used. No special integrated circuit has been necessary for this purpose.

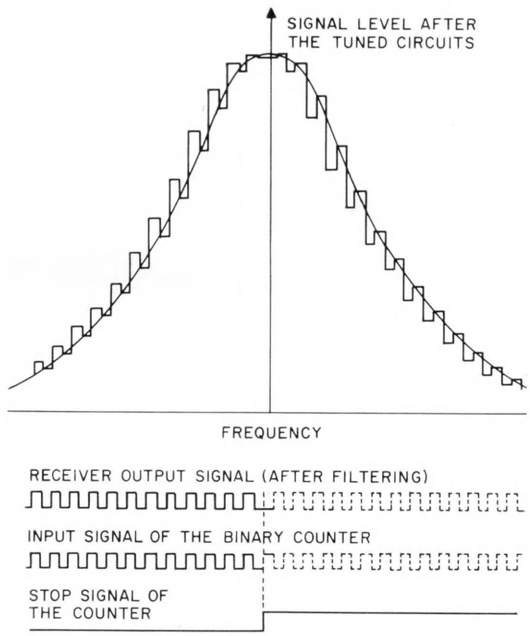

Figure 7—Varactor method of tuning the input receiver circuits to the desired signal frequency.

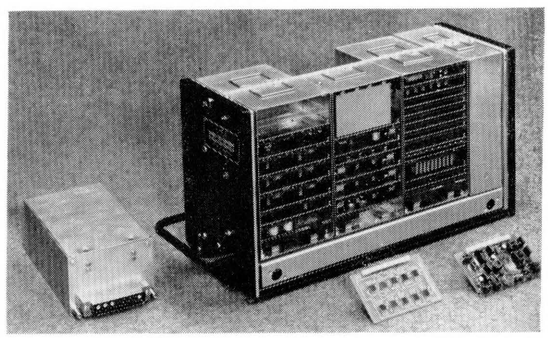

Figure 8—Modular construction.

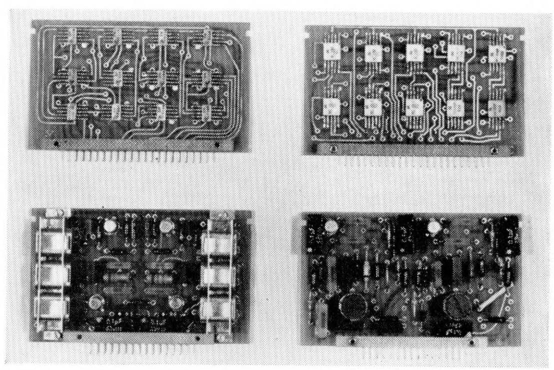

Figure 9—Sample circuit boards showing both integrated circuits and separate components.

6.3 Possibilities for Improvement

The oscillators in each synthesizer subrange could be made on thin films with a Wien bridge circuit. However, the quality of the signals from such resistance-capacitance oscillators is not satisfactory as they produce greater phase jitter than do inductance-capacitance circuits. This design had to be rejected.

The band filters using crystals in a ladder configuration can be made in monolithic form on a single quartz crystal blank by appropriate shaping of the electrodes.

The power consumption of the equipment will be reduced when fast integrated circuits having low power consumption appear on the market.

In its present version, the equipment has a low-power-consumption oven to stabilize the frequency of the reference quartz oscillator to within a relative accuracy of 10^{-7}. For certain requirements for which an accuracy within 2×10^{-7} is adequate, it is possible to discard the oven and use a compensation circuit with the advantage of instantaneous operation and lower power consumption.

7. Conclusion

The extensive use of logic circuits is apparent from the following list of components in the equipment.

Components	*Number*
Integrated circuits	85
Transistors	117
Diodes	93
Capacitors	489
Inductors	100
Resistors	550

The excellent reliability of monolithic integrated circuits together with the important part played by them in this equipment makes it possible to forecast that the reliability of such equipment will greatly exceed that of a unit fulfilling the same functions and equipped with transistors, conventional components, and mechanical tuning devices.

Furthermore, the cost of labor is considerably reduced since no adjustment is necessary during manufacture for the subassemblies equipped with integrated circuits.

J. Lisimaque was born in Paris in 1921. He obtained the diploma of physicist in 1942 from École Supérieure de Physique et de Chimie.

From 1943 to 1945 he was at C. Lorenz. He joined Laboratoire Central de Télécommunications in 1945 in the Transmitting Department and later transferred to Le Matériel Téléphonique, where he specialized in the manufacture of single-sideband transmitters and their associated receivers.

In 1955 he started work on synthesizers and mobile single-sideband equipments in the high-frequency band, and he is now project manager for the development of single-sideband portable and airborne equipment.

Mr. Lisimaque is a member of the Société Française des Électroniciens et Radio-Électriciens.

J. L. Ribour was born in Laon, France, in 1932. He received the diploma of engineer in 1955 from École Supérieure des Arts et Métiers and obtained another diploma of engineer in 1958 from the École Supérieure d'Électricité.

He was a radar officer in the French Navy from 1958 to 1961. He then joined Le Matériel Téléphonique, where he worked on the development of mobile single-sideband equipment in the high-frequency band.

He is now specializing in the study of frequency synthesizers in the high- and very-high-frequency bands.

Design of Medium-Speed Data Transmission Systems

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1. Introduction

This article briefly describes the measurement and computation programme which was undertaken to develop a medium-speed data transmission system.

At the time of the initiation of the work 8 years ago, there was little available knowledge on the transmission of digital information, except that relating to low-speed telegraphy. It was recognized, however, that data would need to be transmitted at much higher speeds and that there would be a requirement for much greater accuracy. Although it was more difficult to determine the forms in which data would be presented and the ways in which it would be handled on reception, time has shown that there are many different applications.

It was correctly anticipated that the signal level at the receiving station would have a serious effect on the errors, and it was also obvious that the bandwidth of the circuit and the type of switching employed would also have an influence.

2. Measurement Programme

There were many design parameters from which the most appropriate were difficult to select until some statistical information became available. However, it was found possible to design a test programme which was reasonably flexible yet capable of extension. As an example, the programme was designed for application to blocks of any size and a range of modulation rates. Trials were carried out over a wide range of circuits. The earlier tests employed frequency modulation up to speeds of 1200 bits per second and were subsequently extended to 2000 bits per second with phase modulation. Another programme of tests was based on 8 parallel channels each of 75 bits per second. The use of a serial stream for testing made it unnecessary to make an early choice between duplex and half-duplex forms of operation; it also avoided any necessity to choose the precise form of synchronization or block size.

Field measurements quickly disclosed the tendency for errors to occur in bursts; it was soon appreciated that to obtain significant results of error characteristics it was necessary to have a series of samples totalling at least 5000 errors. This quantity is essential to permit a significant analysis being made of the distribution characteristics of the errors.

The relationship between error rate and received level was quickly established, as was the fact that the error rate did not increase linearly with the bit rate. It might be expected that each error at 250 bits per second would produce 2 errors at 500 bits per second and 4 errors at 1000 bits per second. With single errors, it was observed that the incidence of noise was frequently of such short duration that it still affected only 1 bit at the higher rates. On the other hand, line interruption or short circuits produced error bursts, and the higher the modulation rate the higher was the number of errors in the burst.

Having established that a reasonable receiving level provided surprisingly good results, it was found possible to obtain a realistic comparison of the typical error rates for a large sample of leased and switched circuits.

3. Block Size

The question of the optimum block size proved of great moment as there was obviously interest in small blocks containing 1 character, intermediate size blocks of about 250 bits for duplex systems, and larger blocks for half-duplex systems. Whereas comparative values could be established for any parameter, it became clear that conditions such as message length and line length were of paramount importance. The method of presenting and subsequently processing the transmitted data also had a bearing on the subject. In very broad terms it was found that the provision of check bits per character did not provide the same degree of protection for line transmission as for terminal handling. The addition of 1 parity bit per character left about 20 per cent of the erroneous characters undetected. Even 2 parity bits per character were inadequate, and better protection was given by a combination of row and column checking. Rather paradoxically it was found that in many tests the protection was better for large blocks than for small blocks, despite the fact that the percentage redundancy was smaller.

Increasing the block size to assist the checking is clearly expensive in terminal cost and inefficient as regards line utilization. Fortunately, the process of checking by a cyclic code was found to have the dual merits of needing much less redundancy and of being capable of providing any desired degree of protection according to the number of check bits provided. The cyclic code is suited to blocks of 100 bits or greater but unsuited to a single character of fewer than 10 bits. It was also recognized that a block of 250 bits is unsuitable for very short messages. It may consequently be found advisable and efficient to employ a short block for short messages and a longer block for long messages. Should the daily traffic involve a large number of short messages, the inefficiency of the short block is rather objectionable, and greater efficiency can be obtained by sending a number of short messages in the form of one long message with larger blocks.

The optimum size of block for duplex operation is decided to a large extent by the maximum loop propagation time; this determines the interval elapsing before the sending station knows whether or not a block must be retransmitted. A block size of 240 bits provides a reasonable compromise for typical national toll connections and allows the effective information transfer speed to be better than 90 per cent of the modulation rate.

There are inter-continental applications for which a much longer propagation loop time such as 1 to 1·5 seconds should be provided, and for this case a more suitable block size would be 480 bits.

It is recognized that these long connections will be expensive, and the larger block size means a longer repetition cycle for error correction. When these long connections are switched, the block error rate will generally be greater than with leased circuits, and the messages will tend to be shorter, but the loop propagation time necessitates the larger block. The same characteristic about message length is also applicable to national connections, but the uncertainty as to the propagation loop time of the route selected makes it essential to provide a reasonable time margin which will be adequate for all national connections. There is also the likelihood that in many switched connections the quality of the connection will be checked by speech before "going over" to the transmission of the data message. If the connection is obviously noisy it should be changed before data transmission commences.

For half-duplex operation, the most effective transfer speed is obtained with blocks of 1000 or more bits, but there is also some interest in smaller blocks, admitting the less efficient use of the line, to reduce the expense of storage equipment. The half-duplex operation has the fundamental advantage that the presence of echo suppressors can be accepted, although with some penalty. Recently, however, it has been recommended that echo suppressors should be disabled on data calls, and hence simultaneous signalling in both directions presents no difficulty for half-duplex operation.

4. Error Control and Correction

Error control is seen to involve several related matters. When circumstances permit, correction by retransmission is advisable. It incurs the minor penalty of occasional delay and the need for a backward supervisory channel.

The lower efficiency of check bits per character can be overcome by adding a signal quality detector which has a very good chance of indicating multiple errors which could remain undetected by parity checking alone. While the signal quality detector may ask for repetitions unnecessarily when the signal is disturbed but not incorrect, this is not really objectionable for short messages and neither is the fact that the percentage of retransmission is increased.

There are many applications over both leased and switched connections for which the user will favour the arrangement which gives the quickest and most accurate transfer of the data. In the case of leased connections, this is important, because computer or other processing may be held up until the information is all received. There may be some overall period available for both the transmission of the data and the subsequent computation, and consequently time lost in transmission may have to be recovered by faster computation. In the case of switched connections, it must be assumed that the daily traffic is probably insufficient to justify a leased circuit; the user will nevertheless still be concerned to reduce the charge for the switched connection by the rapid and accurate transfer of the information.

A third application is the use of data transmission techniques for signalling between communication switching centres. The procedure to be recommended will depend on the loop propagation time and the bit rate to be used. Future speech transmission systems using digital modulation will normally be able to assign a bit stream at 8 kilohertz for signalling and, when the loop propagation time is less than 10 milliseconds, it is possible to repeat each signal several times or to use an information feed-back process for checking. In the case of larger circuits, the propagation loop time is likely to be much larger and this will certainly be the case with geo-stationary satellites. The high cost of the signalling circuit makes it undesirable for the traffic loading to be increased by multiple transmission of the signals. The possibility of using checking bits generated according to a cyclic code is being studied by Study Group XI of the International Telegraph and Telephone Consultative Committee (CCITT).

The subject of error detection and correction has been studied extensively particularly in respect to the sophisticated cyclic codes which provide very good protection, but yet require remarkably few additional check bits during transmission. A data block of 240 bits can be protected by only 12 check bits in a cyclic code, whereas the row and column method needs approximately 4 times as many check bits, and the character-by-character arrangement needs more than 6 times the redundancy.

The investigation into the security of cyclic codes has been founded on the pattern of errors measured during the field trials. By a process of determining the distribution of separations between errors, it has been possible to generate from random numbers a data stream which includes errors whose separation corresponds closely to the measured patterns. A computer programme has been employed to enable the equivalent of a 12-month field measurement to be carried out in a few hours. The comparison of the relative performance of the different cyclic error-detection codes requires such long trials because the failures are so infrequent.

Figure 1 illustrates typical block error rates for transmission over switched and leased connections. The basic error rates vary with every circuit and usually vary during the 24 hours, but the values shown are typical for a large number of connections. Figure 2 illustrates the reduction in the undetected error rate by the use of cyclic detection codes with different numbers of elements. It will be noted that the reduction is greater in the case of switched connections. The service will normally be better on leased connections owing to the reduced error rate as shown in Figure 1.

It is indeed a matter of importance to the user to be guaranteed reliable service during normal conditions, but also to know that service requirements are adequately protected during abnormal conditions. There will undoubtedly be times when a connection is interrupted during the transmission of data. The user does not expect to have to watch the progress of the transmission, but expects to be warned when there is a hold-up. If the interruption is only of a few minutes duration, it is highly desirable that the retransmission should start automatically without introducing the delay and the risk of error which would result from human intervention. The terminal equipment should be designed to recover synchronization if this is lost. It is necessary that blocks of data are neither duplicated nor omitted as a consequence of a long interruption or the need to re-establish the connection. The use of block sequence numbers safeguards that the blocks are accepted in the proper order and it also assists in the rejection of erroneous blocks in noisy circumstances.

Another safeguard introduced to minimize the chance of accepting an erroneous block is the fail-safe feature of the repetition cycle including the backward channel. As an example, when the circuit is open owing to some interruption and the receiver is offered trash, every incorrect block is likely to be rejected on account of the non-arrival of the backward supervisory signal.

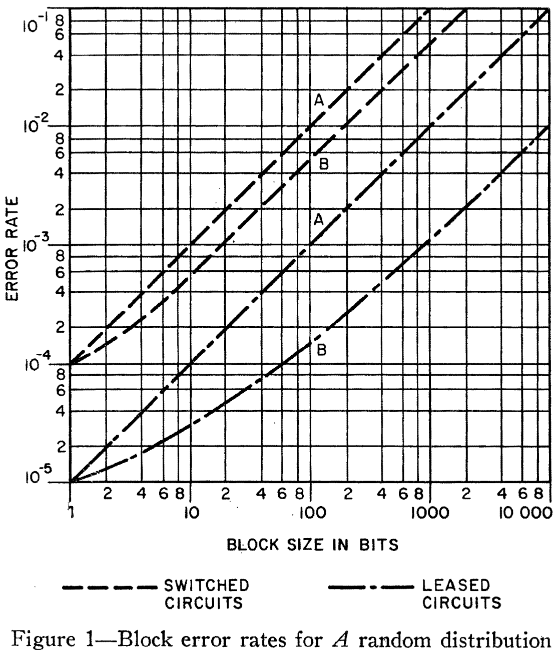

Figure 1—Block error rates for *A* random distribution and *B* measured distribution.

For longer interruptions, the process will normally involve establishing a new connection and recommencing transmission. There will also be the case in which the data transmission is being frequently delayed by line interference; the quick solution for the switched connection is to seek another circuit. A connection which is too noisy for the transmission of data can be recognized without difficulty because the noise would result in a normal telephone connection being released and re-established.

5. Faster Transmission

The study of the data receiver design has led to the recognition that operating margins could be greatly improved by eliminating the wide variation in the characteristic of the received signal. Interesting work has been carried out on minimizing delay distortion by automatic equalization of the connection. The received signal is so much improved by this process that investigations are in progress to increase the information transfer rate of a single telephone channel by using multi-level signals. With multi-level technique, each pulse can carry 4, 8, or even 16 bits of information and hence the information rate would be significantly increased. It is envisaged that error correction would be provided by retransmission.

6. Conclusion

Operational experience has shown that data transmission in blocks with correction of errors by retransmission is eminently suited to the needs of many users with a load pattern of something between 1 to 50 million characters per day. Error detection based on a 12-bit cyclic code and a 4-bit sequence number provides a service which is so reliable that the user is scarcely aware that errors do occur in transmission and are automatically corrected. More check bits would increase the security, but the quality of service is already such that it is unlikely that any further increase would even justify the small extra cost and reduction in information transfer speed.

The correction by retransmission inevitably involves some delay; if the possibility of delay is unacceptable, it is necessary to transmit sufficient redundancy to allow automatic correction, a process which can only tolerate a certain amount of message distortion. The needed increased redundancy involves a higher modulation rate and more expensive terminal equipment. Higher-speed transmission using more bandwidth than that provided by a single speech circuit is unsuited to block transmission because of the short loop propagation time which can be admitted for a block that is emitted in a few milliseconds.

The user with less than a million characters to transmit daily is less concerned with a reduced information rate because on short messages much of the time is needed for establishing the data connection. The achievement of block or character synchronism will depend on loop propagation time, but it should always be more quickly established with a character or short block. A character-by-character form of data transmission needs a device such as a signal quality detector to back up the character parity check. This detector will inevitably reject some good characters because the signal level is abnormal. For short messages this extra transmission is acceptable.

Another procedure which has been studied for users with a small amount of traffic is the introduction of a special block-end signal. Such a signal allows short messages to be terminated before the block ends, and it also allows longer messages to be divided into blocks of fixed length. Safeguards needed to guard against the imitation or distortion of this signal are more complex than the processing of blocks of uniform length.

7. Acknowledgment

During the design period, valuable assistance has been received from many sources, particularly from engineers of the British Post Office and other Administrations. Many of the tests have included international lines, and for all the test connections there has been the need to arrange for a brief procedure in preparation for the series of measurements.

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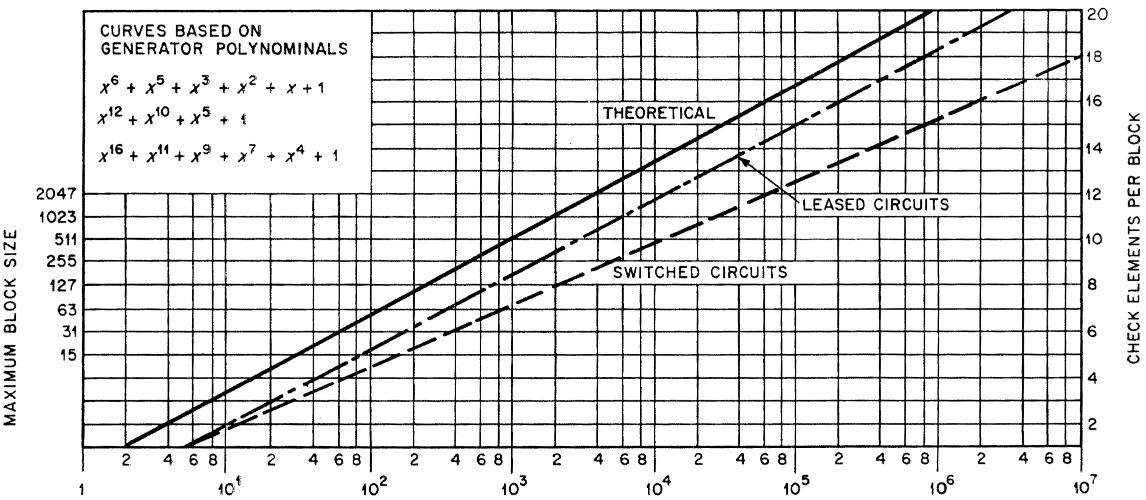

Figure 2—Improvement factor of cyclic codes.

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E. P. G. Wright joined Standard Telecommunication Laboratories on its formation after many years in the Switching Division of Standard Telephones and Cables. He directed various data processing and transmitting developments; among these was an extensive programme of measurement and analysis of errors during transmission of data over a series of leased and switched connections. Computer programmes were subsequently developed to simulate the occurrence of errors and thereby allow the efficiency of different error-detection codes to be compared. The results of this research have been used for various applications such as the Signalling System 6 of the International Telegraph and Telephone Consultative Committee (CCITT).

Alan D. Marr was born at New Southgate, London, in 1931, and graduated with the degree of B.Sc. at London University in 1954.

He joined Standard Telecommunication Laboratories in 1951, since when he has been engaged on various facets of the work associated with switching systems and data transmission. He has studied various forms of coding for error control purposes and is the author of 4 patents.

Earp, French, and Heaton-Armstrong Honored

The Institute of Electrical and Electronics Engineers recently advanced the following three engineers of the International Telephone and Telegraph System to its highest grade of membership, Fellow, thus placing them among the approximately 2 percent of its 160 000 members so honored. Their citations are given below.

C. W. Earp of Standard Telephones and Cables "for his contributions to the art of radio direction-finding antenna systems."

H. A. French of ITT Federal Laboratories "for the concept and development of microwave communication techniques and equipments, and his engineering leadership in the system engineering and implementation of microwave communication systems."

L. J. Heaton-Armstrong of Standard Telephones and Cables "for contributions over many years to the design and manufacture of radio communication equipment for both civil and military use."

Himmel Honored

Leon Himmel, Vice President for Avionics of ITT Federal Laboratories, was named Honorary Vice President of the American Society for Zero Defects in March 1967.

GH 205 And GH 206 Medium-Speed Data Systems

C. E. BLOCH

Standard Telephones and Cables Limited; Enfield, England

The work of Wright and others had shown both the feasibility and desirability of cyclic coding as a means of error detection in medium-speed data transmission systems. The physical embodiment of these ideas into commercially viable systems led to the development of the *GH 205* and *GH 206* equipments.

While the error detection technique was thus established, the resultant error control procedures remained to be solved. Accordingly, certain fundamental decisions were taken at the outset on the parameters of the systems to be developed. Paper tape was initially chosen as the data source and sink medium. The block size was chosen as 256 bits of which 240 bits represent the information content, 12 bits the protective redundancy, and 4 bits were designated service bits. The protective polynomial chosen is of the form $X^{12} + X^7 + X^2 + 1$, which it was predicted would give an average improvement factor of 15 000. The equipment is designed to provide a code "transparent" channel, such that all transmission errors are removed, and complete independence of input coding is maintained.

The block diagram (Figure 1) shows the organization of both the send and receive terminals of the *GH 205*. The system consists of a data source at the send terminal, which can be either punched paper tape, punched cards, or computer, controlled by the data source control. The data are converted to serial form in the parallel-to-serial converter and stored in a ferrite store. The latter is addressed and controlled by the logic contained in the store address and control module.

The block timing is derived from the block control, which defines the three periods comprising a transmission block, namely, the sequence number time (4 bits), the information time (240 bits), and the redundancy time (12 bits). In addition it also accepts a pulse from the address counter that is within the store address and control, defining the end of the information time. The sequence-number generator provides the encoded sequence-number information to be inserted at the start of each block, and in addition a sequence control function is performed by giving to the store address and control the address of that section of the store from which the next block of information is to be extracted.

The essential decision-taking element of the equipment is the transmission control. This accepts signals from the modem on the supervisory channel and decides on the manner in which the sequence numbers shall change and whether information will be transmitted or not. The redundancy generator provides the 12-bit protective code which is added to the end of each block. It also generates the pattern used to obtain block synchronism between the send and receive terminals. The operating lamps, alarms, and keys are on the manual control panel.

The receive terminal comprises a data sink, which can be either a paper tape punch, card punch, high-speed printer, or computer, operating under the control of the data sink control logic. The serial-to-parallel converter alters the serial bit stream obtained from the store into parallel characters for the data output. The store operates under instruction from the store address and control.

Incoming information from the receive modem is examined and the relative clock rate between send and receive terminals adjusted by the bit synchronizer. The receive clock is thereby either advanced or retarded to ensure that each incoming bit is examined at its centre point. Block synchronism is obtained by the block control which also functions, as in the send terminal, as a timing signal encoder, defining the basic periods within a block. A sequence number checker verifies the incoming sequence number against an expected code, and the redundancy check determines whether the data have been corrupted during transmission. The signals received from the latter two units are interpreted by the transmission control which determines the signal to be returned to the send terminal over the supervisory channel, and the action to be taken at the receiving terminal in anticipation of the resultant change in the sequence of data. The signals received from the manual controls and the alarms displayed on the control panel result from action taken by the transmission control.

When a manually initiated transmission is required, the operators establish a voice connection between the send and receive terminals. With the peripheral equipment ready, or computer in the data-transmission mode, the operators switch from speech to data, thereby passing "request to send" signals to the modem. The modems respond with "clear to send," at the same time transmitting tones over the line. When the send terminal has received the supervisory signal and is in the data mode itself, it will start to send synchronizing blocks. These

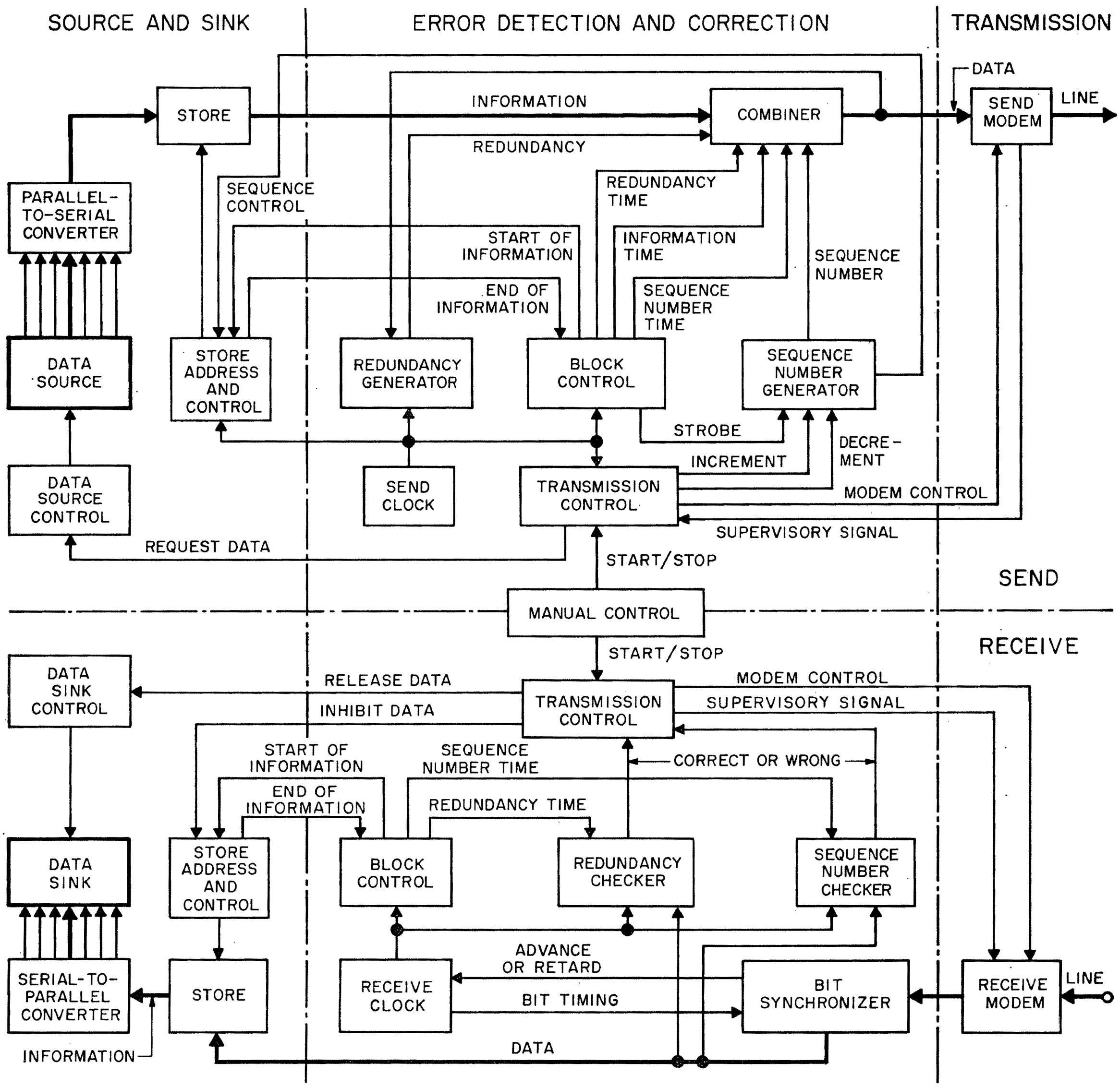

Figure 1—Block diagram of the *GH 205* equipment.

blocks consist of 244 bits of alternate *1* and *0* reversals, followed by 11 *1*'s and a *0* in the last bit. At the receive terminal the incoming reversals are utilized to ensure that bit synchronism is obtained, by advancing or retarding the position of the timing wave pulse to strobe each incoming bit in the centre. In addition the block control at that terminal examines the message for the 11 *1*'s and a *0* to determine the correct element for block synchronization. Immediately block synchronism has been attained the signal on the supervisory channel requesting a repetition (*RQ*) is removed and transmission of information commences 1 block later.

Information is read at high speed into the ferrite store in blocks of 240 bits. All information transmission is from the ferrite store, with sequence numbers prefixed and redundancy appended at the end of the information. The latter is checked in the receive terminal for transmission errors. To ensure that the correct synchronizing block is generated, the redundancy generator is primed at the beginning of every block with a starting pattern such that with a pattern of 244 bits comprising alternate *1*'s and *0*'s, the redundancy will consist of the pattern of 11 *1*'s and a *0*.

In the event of a detected error the receiver transmission control will initiate an *RQ* (request for retransmission) by sending binary *1* on the supervisory channel for $\frac{1}{4}$ of the following block. When the sending terminal receives an *RQ* in the block following the error block, it will stop transmitting information in the centre of that block and send 1:1 reversals for the remainder of the block. The following block will be a synchronizing block and this will be followed by a repeat of the information originally in error, with the same sequence number as when first transmitted.

The receiver, on detecting a block in error, will completely ignore the following block, check the synchronizing block, and if that is correct will proceed to accept the repeat of the erroneous block. The incoming information is stored but will only be output to the data sink when it has been verified. If, however, the receiver determines that an error has occurred in a synchronizing block, resynchronization must take place before it continues to accept information. By placing a continuous *RQ* on the line, the send terminal is instructed to send further synchronizing blocks until the two terminals are once more in step. Alarms are provided in the event of parity errors at the send terminal. Also, if after 8 successive attempts the terminals have failed to transmit a block of data due to line noise, a retransmission alarm occurs and the operators must revert to speech.

Facilities also exist for automatic answer of either a send or receive terminal from a remote attended point.

Figure 2 shows a *GH 205* twin terminal equipped with Facit tape reader and tape punch and fitted with the logic for interfacing with a Honeywell *H220* computer.

A careful examination of the block diagram of the *GH 205* twin terminal shows that there is a commonality of equipment between the send

Figure 2—The *GH 205* equipment.

and receive terminals, which in an either-way terminal could be effectively eliminated.

The *GH 206* is just such a system in which this duplication is eliminated to cater for either-way data transmission requirements, and where system changes are introduced to reduce the overall hardware content, without at the same time sacrificing any of the sophistication and subtlety of the error protection. The block diagram in Figure 3 shows the organization of the *GH 206*.

A combined input/output unit, to provide the data source and sink, is connected across a standard interface, with a combined send/receive error detection and correction unit. The entire approach has become a modular concept based on a common error detection and correction unit designed to handle a wide range of peripheral equipments such that any special-purpose engineering required for matching peripherals to the error detection and correction unit would be confined to the input/output unit. Additionally, such advantages as may pertain from having a data source with inherent storage, such as bi-directional paper tape readers or bi-directional incremental tape recorders, can be incorporated as desired.

The message format has been altered for the *GH 206* to give 3 sequence number bits followed by 240 information bits, one decision bit designated the cancel bit in position 244 of the block, followed by 12 redundancy bits. In addition, a more complex synchronizing procedure has been established in which three forms of synchronizing block have been defined. These are (A) a start-of-message block, (B) a synchronizing block, and (C) an end-of-message block.

These three blocks have an identical information content but vary in their sequence numbers. The information content comprises a combination of 1:1 reversals, and 2:2 reversals for the last 30 elements of the information period of the block. In other respects the system has been made identical to the *GH 205* in its retransmission cycle and line signalling procedures.

Figure 3 shows a block diagram of a *GH 206* either-way medium-speed data transmission system. Information derived from the data source is serialized in the input/output register. If the data source has a bidirectional facility, then no additional storage is required for the send facility, but if not, the information is fed via straps A to the store. Under the instruction of either the store address and control or the data control, information is passed into the error detection and correction section and, during the information time, the combiner transmits the information to line via the modem. A sequence number generator generates the sequence number during the sequence number time as defined by the block control, and the redundancy generator, by examination of the combiner output, generates the protective pattern appropriate to the block. Overall control of the system is vested in the transmission control, which interprets signals received from the control panel and the supervisory channel. The various synchronizing blocks are generated by the synchronizing pattern generator, and the cancel bit is inserted by the transmission control.

When operating in the receive mode the incoming data are regenerated in the bit synchronization logic and strobed in the centre of the element by the receive clock. The sequence number is checked against that expected in the sequence number check logic while the redundancy generator derives the check pattern appropriate to the received signal for comparison with the received redundancy in the redundancy checker. The state of the cancel bit is determined by the cancel bit checker, which instructs the store address and control (via the transmission control) when to output to the input/output register and from there to the data sink under control of the data control. When synchronizing blocks are being received, the synchronizing pattern generator output is checked against the received pattern in the synchronization checker logic.

Operationally the systems differ in that initial synchronization is essentially a manual process

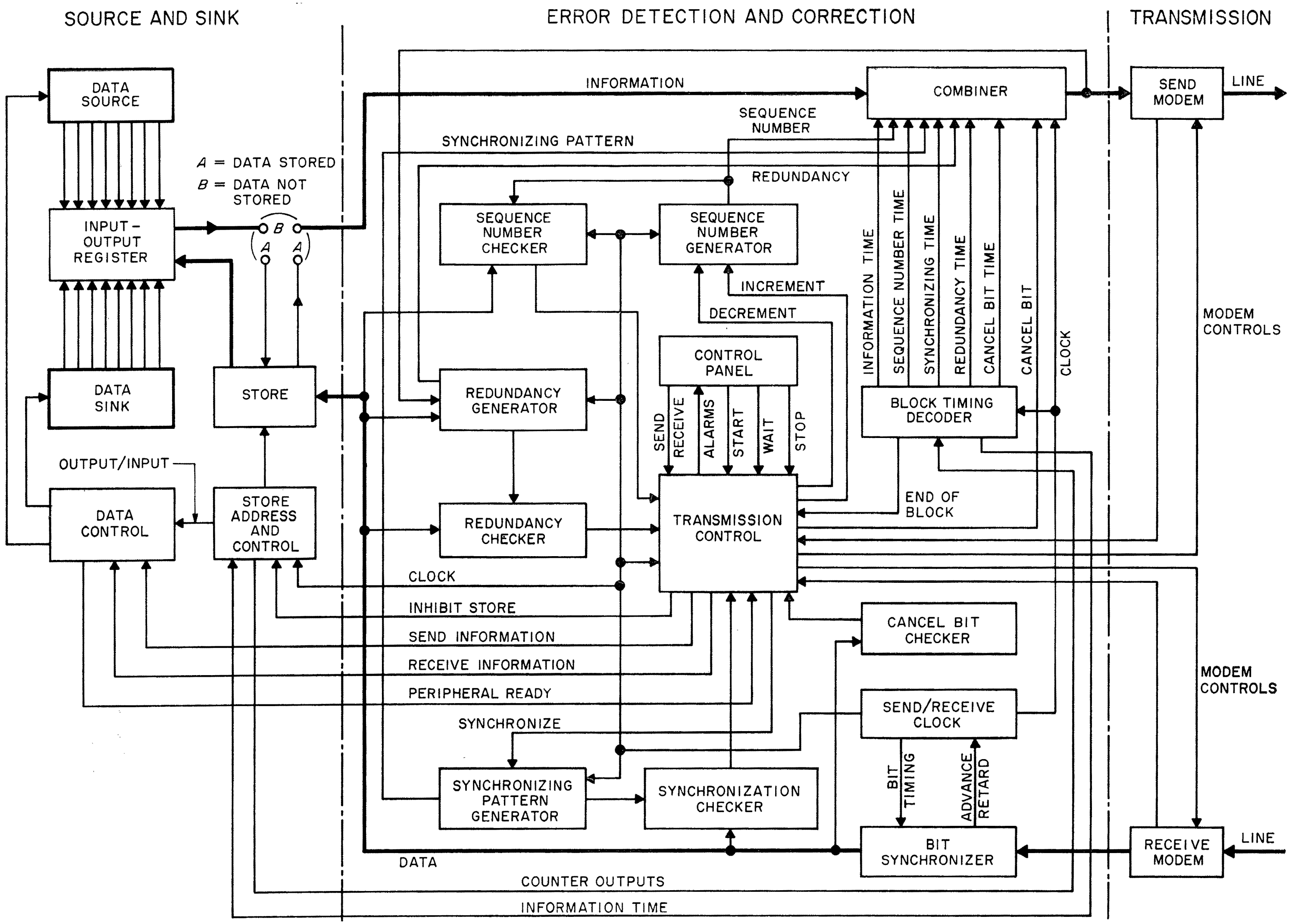

Figure 3—Block diagram of the *GH 206* equipment.

in the *GH 206*. The operator presses the START DATA key at the send terminal, having previously established the call, while the receive terminal operator presses the RECEIVE DATA key. The send terminal will send start-of-message blocks, which serve to reset the receive logic and establish initial synchronism. When the two terminals are synchronized the SEND DATA button lamp will flash, and when the button is pushed information transmission will commence.

The purpose of the cancel bit is to provide advance warning to the receive terminal of anything amiss at the send end. The resultant action is to ignore the information content of the following block. It is used to warn the receiver of any *RQ* signals received, and thus helps to distinguish between genuine and false requests for repetition, and it can also be used as a warning of incorrectly transmitted parity as a result of peripheral errors.

By using the input/output register to feed information directly from data source to data sink, the equipment can operate in the copy mode. This contrasts with the *GH 205,* which loops the input and output wires to achieve this facility,

Figure 4—The *GH 206* equipment.

but this also can be used to fully check out a complete twin terminal. A *GH 206* twin terminal is shown in Figure 4 with Teletype *BRPE 110* paper tape punch and Tally bi-directional paper tape reader. The equipment is housed in a desk-height cabinet and uses ITT standard equipment practice for card mounting.

Experience to date on both United Kingdom switched circuits and transatlantic cable circuits has indicated that the predicted error improvement factor with both equipments is slightly pessimistic due to the additional safeguards incorporated in the systems. Since the peripheral equipment used will not give a performance which is better than the residual error rate of the equipment a quantitative assessment becomes unrealistic. However, the improvement factor is certainly in excess of the predicted figure of 15 000. In fact statistics gathered from some of the 80 systems in present use have shown that a character error rate of 1 in 40 million has been realized. These figures have been gathered during the period from August 1966 to March 1967, although actual working experience does extend over four years and represents 28 system-years of working.

The present range of equipments will allow their use over circuits with a loop propagation delay of not more than 200 milliseconds at a speed of 1200 bauds. However, equipments have been modified by increasing the store size and have been used over both synchronous and non-synchronous satellite systems to give the same high standard of system integrity. When used on circuits with echo suppressors of the disabling type, both data terminals will allow the use of recommended procedures of the International Telegraph and Telephone Consultative Committee (CCITT) for the disabling of such echo suppressors, in particular when automatic calling or answering is incorporated.

The use of automatic answering facilities with the *GH 205* is rendered possible by the completely automatic nature of both start-up and close-down procedures and it is noticeable that during operation, even under manual control of the transmission path, the operator is not aware of intermittent line interruptions, other than the check in data flow when errors are being corrected. Alarm facilities are however incorporated to ensure that lengthy disconnections are brought to the attention of the operator or in the automatic case to close down the link.

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After a 2-year graduate apprenticeship in the United Kingdom he joined South Africa Philips where he was Head of the Industrial Applications Laboratory.

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Filter Design Tables and Graphs

Erich Christian of ITT Telecommunications in Raleigh, North Carolina, and Egon Eisenmann of Telefunken AG in Backnang, Germany, are the authors of a recently published book on "Filter Design Tables and Graphs."

The introduction includes definitions of terms and a statement of the problem, normalization, band transformations, standard approximations of the reference lowpass, realization procedure, design of filters between arbitrary terminations, and numerical examples. It is followed by the main part of the book consisting of tables and nomographs used in the design of filters of the Butterworth, Chebyshev, and Cauer types.

The book is 8.5 by 11 inches (21.6 by 28 centimeters) and contains 312 pages of text and drawings. It is published by John Wiley & Sons, 605 Third Avenue, New York, New York 10016, at $9.95 per copy.

Pulse Code Modulation for Automatic Switching of a Military Network

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1. Definition of the Problem

A military tactical telephone network should permit combat-zone units, no matter where located and despite possible partial destruction of the network, to set up communications with one another with complete security and by automatic means.

These severe conditions can be met only by maximum reliability and flexibility in operation. The network should be adaptable to many possible modifications of traffic, recognizing the trend away from telephony towards transmission of digital data even at very high speed.

The application of pulse code modulation promises excellent coordination between both transmission and switching.

2. Advantages of Pulse Code Modulation

Pulse code modulation replaces analog signals by purely digital signals for which a signal-to-noise ratio of 10 decibels is sufficient for safely recognizing the useful signal. It is therefore eminently suitable for a network having various means of transmission that are subject to great disturbances. For radio transmission in particular, it permits utilization of the same frequency channels for links that are geographically so close that other types of modulation would fail because of excessive crosstalk.

It should also be noted that it will operate with purely electronic equipment for which the required technical reliability has been adequately demonstrated. This is not the only advantage of pulse code modulation.

For instance, it permits the digital data to be sent at high speed. The standard rate is 48 000 bauds per channel. This rate cannot be realized completely because of losses of information if the system is subjected to intense interference, or losses may be introduced by the resynchronization methods described later. However, despite these potential losses of information the use of redundant codes permits the detection, or even the correction, of errors, and transmission rates of 20 000 or 30 000 bauds can be reached with very great security.

This great transmission capacity can be used for the exchange of information between units inside an exchange as well as between exchanges in the network.

This transmission within an exchange leads to a simplification of equipment. In the network it improves the operational reliability by permitting the use of a particularly attractive method for routing calls.

3. Network

The tactical network of the combat zone that we studied for the French Army is a fully automatic mesh network having transit exchanges or zone exchanges Z at its nodes (Figure 1) to which the local exchanges LE are connected to serve the subscribers through small switching units called concentrators. The latter may be at various distances from the local exchange.

All these switching centers are interconnected by multiplex pulse-code-modulation highways. Each such highway comprises 23 communication channels and a synchronization channel. A concentrator is linked to its local exchange by a single multiplex highway. A local exchange whose maximum capacity is 6 pulse-code-modulation highways is linked by one or more such highways to at least two transit exchanges whose total capacity is 18 pulse-code-modulation highways.

4. Routing of Calls

4.1 Principles of Search

Each subscriber of the network possesses a specific directory number. The numbering is of the closed type, that is, the number of digits is constant for all directory numbers. Each subscriber can be placed anywhere in the whole network while keeping the same directory number.

In each exchange of the network directly connected to the concentrators (local exchanges), the numbers of all the subscribers connected to the line equipments are written in a semipermanent memory.

The full number of the called subscriber is received by the local exchange in which the call originates. An examination of the memory determines if the called subscriber is connected to this exchange.

If so, the called line is tested and if free is connected directly with the calling subscriber.

If the called subscriber is not in the originating exchange the directory number is sent towards all the other exchanges over free channels on the multiplex highways connected to the originating exchange.

As the called number spreads through the network, each local exchange searches its memory to determine if it has that number.

The local exchange serving the called subscriber sends a return order towards the calling exchange over the path through which it received the call.

This search not only finds the called subscriber but also establishes the routing of the call, and any free path between the calling and called exchanges is seized automatically.

4.2 Details of the Search for a Called Subscriber

Take as an example, the mesh network shown in Figure 1.

At each node of the network the zone exchanges *Z11, Z12,. . ., Z34* are set out.

Each *Z* is linked to the nearest 4 *Z* by 4 routes of 1 or more highways and also to various local exchanges.

Two local exchanges *LEA* and *LEB* are shown in Figure 1, each having 2 concentrators, *CA1* and *CA2,* and *CB1* and *CB2,* respectively.

The setting up of a connection between *LEA* serving the calling subscriber and *LEB* serving the called subscriber will be examined.

Three types of orders are used for the search for the called subscriber and the setting up of the connection.

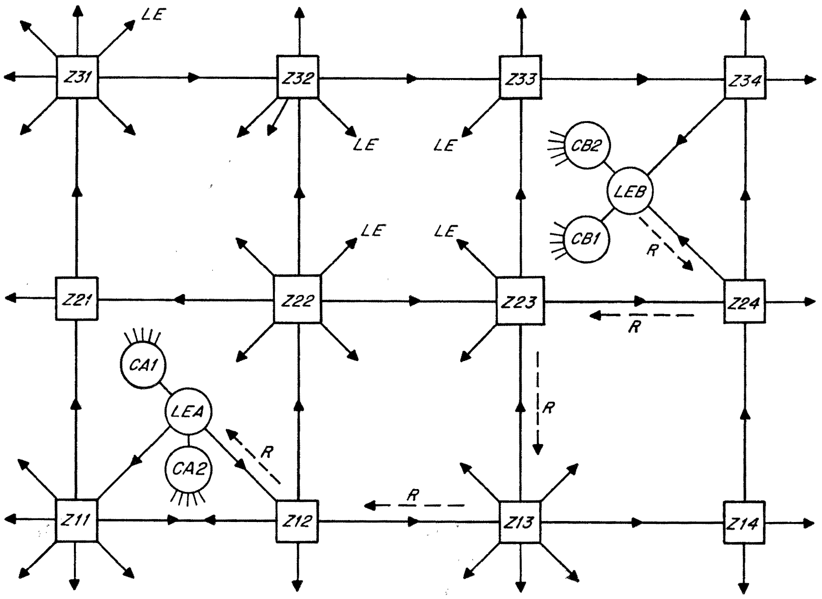

Figure 1—A typical mesh network having transit or zone exchanges *Z* at the nodes to which local exchanges *LE* are connected. Concentrators *CA* and *CB* are connected to the local exchanges.

(A) A search order coming from the originating exchange spreads throughout all the exchanges of the network.

(B) A return order is sent by the exchange serving the called subscriber.

(C) An end order then comes from the originating exchange.

Each order bears the number of the called subscriber and a code indicating the type of order.

4.2.1 *Setting Up a Connection Between LEA and LEB*

When the dialled number has been received by *LEA,* the semipermanent memory is consulted. If the called subscriber is not connected to *LEA,* a search order is sent to the zone exchanges *Z11* and *Z12* connected to *LEA*.

Each of the exchanges receiving the order sends it to all other exchanges linked to it (*Z* and *LE*) and stores the number of the called subscriber, the search order, and the identity of the highway from which it received the search order.

During the setting up of a connection, an exchange *Z* may receive a search order for the called subscriber several times successively. For instance, the exchange *Z21* receives a search order from *Z11* then from *Z22*. The first search order being stored, the following ones will be ignored.

The search order reaches every exchange of the network that has a free channel connecting it to any other exchange.

In each local exchange, the called number is compared with those of the subscribers served by the exchange.

The local exchange serving the called subscriber, *LEB* in the example in Figure 1, after finding the number in its memory sends a return order over the highway *Z24* from which it received the search order.

The latter in turn sends the return order over the highway from which it was received.

Thus, step by step, the return order goes from exchange *LEB* to the originating exchange *LEA* marking a path through the network: *LEB, Z24, Z23, Z13, Z12,* and *LEA*.

In each exchange, the path thus designated is stored.

On receipt of the return order the originating exchange *LEA* in a similar way sends an end order to all exchanges.

This end order sets up the connection between *LEA* and *LEB* through the zone exchanges (*Z24, Z23, Z13, Z12*) marked by the return order and erases the information concerning this call from the memories of all the other exchanges not concerned with the connection.

4.3 Advantages of Method

The advantages of the method include the flexibility of automatic search for the called subscriber and the security provided by widespread routing of the calls.

The automatic search for the called subscriber makes the numbering plan completely independent of the arrangement of the network and of modification of it.

Each subscriber is characterized by a specific number and has complete freedom to move throughout the network. The assignment of a new line consists merely in introducing this directory number into the semipermanent memory of the local exchange concerned. The exact nature of this very simple operation depends on the type of memory used.

The same mobility is also possible for the exchanges. Each local exchange can be displaced with the whole of its subscribers or not, the architecture of the network (zone exchanges, transmission highways) can be completely revised without modification of the numbering plan.

The automatic routing of calls permits maximum advantage to be drawn from the transmission and switching equipments of the network, regardless of what damage may have been done to them.

The security provided by the mesh character of the network assures that a call will arrive as long as a free path remains.

All things being equal moreover, this results in an increase in the possible traffic on the transmission highways, which permits their number or their size to be decreased.

It should be noted that in a network using conventional signalling techniques, the necessity of signalling from the originating exchange to every other exchange in the network would sharply limit the size of the network and its traffic capacity. However, pulse code modulation permits a single channel to transmit 48 000 binary digits per second. This speed provides amply for this redundant signalling even for a large military network having high traffic capacity.

In the prototypes constructed, protection against errors is ensured by transmitting the digits for the directory number and type of order twice.

Directory numbers have 5 digits and the length of an order including the start signal is 16 frames of pulse code modulation.

The signalling channel between two exchanges could therefore handle 500 orders per second for a single direction. A signalling channel will handle the search order and the end order for a call. However, only the channels retained for a call will transmit the return order.

The number of possible calls per second in a network depends on its configuration, and an estimate for an unfavorable case is about 200 calls per second.

For an average length of conversation of 2 minutes, it corresponds to a traffic of 24 000 erlangs, which seems a great deal even for a very big network.

Numerous variants of searching are possible. For instance, the search for the called subscriber can be made in two stages. In the first stage the search is restricted to a part of the network close to the calling exchange. Only if this does not find the called number will a general search be made throughout the network. This avoids blocking of the whole network by short-distance calls, which are often most frequently made in a big network. In another method the called subscriber will be assumed to be in a certain part of the network and the search is first made in this zone. If this does not succeed, a general search is made.

5. Description of Equipment

5.1 Concentrators

The concentrators (shown in Figure 2) have a capacity of 50 subscribers and are linked to the exchange by a multiplex highway.

Speech is sampled at a rate of 8 kilohertz or every 125 microseconds. As each sample is allotted 5.2 microseconds for transmission a multiplex highway accommodates 23 simultaneous conversations and a 24th channel for synchronization.

The encoding of the samples is done in the concentrator by means of a pulse code modulator operating in series logic and supplying a pure binary code of 6 bits (64 different quantization levels). The steps of these quantization levels are not uniform and produce a compression effect. The compression curve of the code versus the signal is shown by three straight-line segments with two different slopes in Figure 3.

The decoder restores the signal with an expansion curve complementary to the compression curve of the encoder.

The subscriber gates which sample the information in the two transmission directions are controlled by a line decoder. The identity of the subscriber to be decoded is stored in a memory comprising 23 lines corresponding to the 23 possible connections.

It should be noted that the direct-current signals corresponding to the state of the line (handset on hook or off hook) as well as the voice-frequency digit signals are transmitted by the same path as the speech signals.

The logic functions of the concentrator are very simple and consist mainly of setting up and releasing a connection between a subscriber and a given multiplex channel. After logic processing, these functions are reduced to the erasing or writing-in of a code in a line of the subscriber memory.

To connect a subscriber to a channel, the exchange sends to the concentrator over this originally free channel the code of the subscriber to be written in the memory on the line assigned to this channel. There is therefore no other blocking than that resulting from the concentration as each subscriber has access to all the channels.

To release the connection of a subscriber with a channel, the concentrator sends onto this channel a code that is characteristic of the releasing function (a code that is normally forbidden in speech) and is identical to the rest code.

The detection of a subscriber placing a new call and the testing of the line of a called subscriber is done from the exchange by successively making brief connections to all subscriber lines to determine the state of each line.

If a subscriber is busy, the identity of the channel with which he is connected is transmitted to the exchange.

Two different types of voice-frequency terminal equipment exist, a 4-wire subscriber line equipment and a 2-wire equipment, permitting the concentrator to work with local or central-battery exchanges.

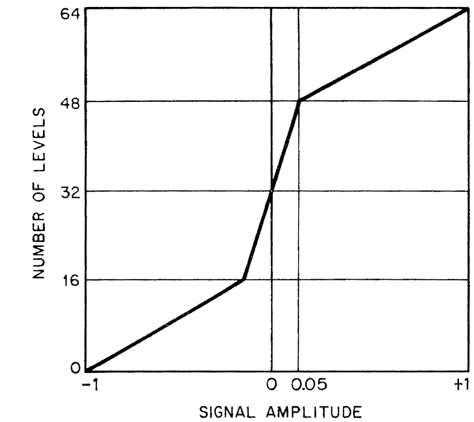

Figure 3—Compression curve of the encoder.

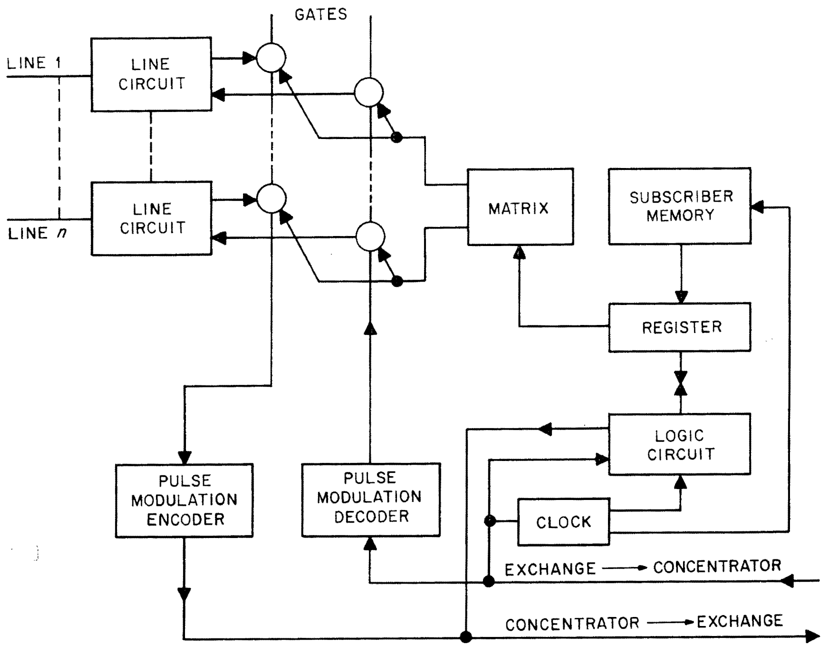

Figure 2—Concentrator.

The concentrator requires 70 watts. The power supply is incorporated in the equipment.

5.2 Transmission

The transmission between concentrators and exchanges or between exchanges is over cable. Repeaters are inserted every 1200 meters (4000 feet) to regenerate the pulses transmitted at the rate of 1152 kilohertz.

5.3 Exchange

The information in series bits may arrive with a frequency that may be different from that of the exchange.

In addition the switching operations are carried out by processing the information in parallel form (the 6 bits for each word being transmitted at the same time).

There are three major equipments that will be discussed.

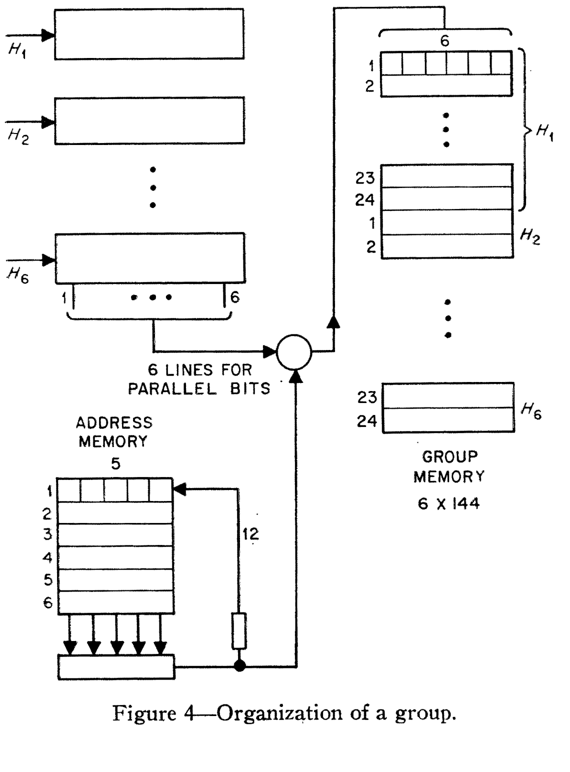

Figure 4—Organization of a group.

(A) Interface equipments between transmission and switching (incoming group).

(B) Switching equipments (local junctors and space switch).

(C) Control equipment with its peripheral units.

5.3.1 *Incoming Group Equipment*

A group having a capacity of 144 channels could serve 6 incoming highways $H_1 \ldots H_6$, each of 24 voice channels $V_1 \ldots V_{24}$ as shown in Figure 4.

Any channel is indicated by associating the identity of its highway with its number in this highway, for instance, $V_{12}H_4$.

The role of the group equipment is to synchronize the information on its arrival in the exchange, to carry out a multiplexing of the 6 highways that constitute a group of 144 channels, and to carry out the serial-to-parallel conversion of the 6 bits for each word.

The synchronizing operation is done in two stages. The first stage consists in using the series-parallel transformation to synchronize pulses word by word. The incoming highways then form a group having in common the 6 outgoing wires of the words in parallel form with words succeeding each other every 0.87 microsecond.

Although the highways will be connected successively, the voice channels will not be in sequence and we may receive V_1H_1, V_5H_2, $V_{11}H_3$, $V_{23}H_4$, V_6H_5, $V_{17}H_6$, V_2H_1, V_6H_2, $V_{12}H_3, \ldots,$.

The second stage consists in rearranging the successive words so that we have V_1H_1, V_1H_2, V_1H_3, V_1H_4, V_1H_5, V_1H_6, V_2H_1, V_2H_2, $V_2H_3, \ldots,$.

This operation will be carried out for each highway in a memory having $24 \times 6 = 144$ cells. The 6 binary digits in which the words of the different channels of the highways are written are stored in the cells corresponding to their row.

The addresses of these cells are given by a 6-line address memory of 5 binary digits. In each line, assigned to one of the 6 highways, is written the number of a channel and, on each readout of the line, this number is increased by 1.

When the number of the 24th channel is read out on a line, the word to be written in the memory should be the synchronizing code. If this condition is not verified, a signal is sent to the central synchronizing circuit to correct the synchronization of the highway.

5.3.2 *Switching Between Groups*

The link between the channels of the different groups is made by means of a space switch and local junctors, as shown in Figure 5.

Each local junctor has access to all the incoming groups and processes 72 connections in time-division multiplex.

The maximum number of groups of 6 highways is three. Added to these groups is a supplementary group called G_4, which is the exchange control circuit.

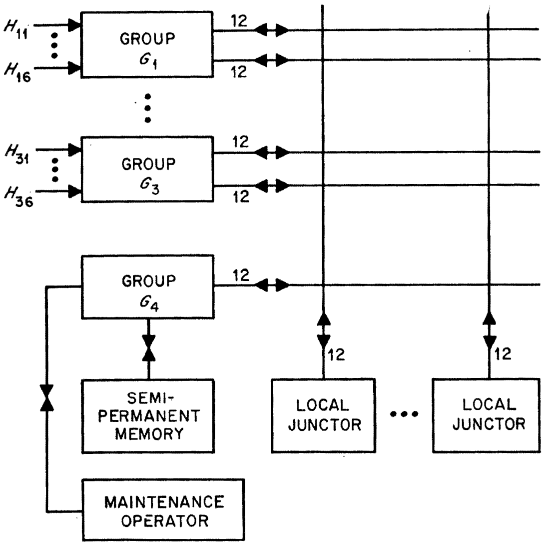

Figure 5—General organization of an exchange.

These groups are interconnected to one another by as many local junctors as there are groups.

A local junctor essentially comprises a 72-line memory of 22 binary digits that are divided into 5 words.

One word of 3 binary digits is for the supervision memory shown in Figure 6. Another single word of 6 binary digits contains the information to be switched in the speech memory. A third word of 7 binary digits defines a time slot out of 72 slots in the time-division switching memory. Finally 2 words each of 3 binary digits give the space selections of the two corresponding groups in the acyclic and cyclic space switching memories.

The space switch has two independent transmission directions. Each intersection point comprises two sets of 6 gates in parallel.

The control of the intersection point, common for the 12 gates, is given by the decoding of the group selection words.

The local junctor works in time division with a cycle of 125 microseconds divided into 144 units of 0.87 microsecond each.

At each time interval the local junctor carries out the time-division switching of one channel of an input. The 144 units of time are divided into two categories; 72 cyclic times corresponding to cyclic readouts and writings of the memory with a clock and 72 acyclic times corresponding to readout-writing by random addressing of the memory.

5.3.3 *Control Circuit*

The connection between the control circuit and the speech circuit is made by using the speech circuit itself and by considering the control circuit as a group with respect to the information that it exchanges with the other groups and with the local junctors.

The control circuit processes any call while taking advantage of the redundancy of the speech circuit, thus providing very great operational security.

The control circuit operates in time-division multiplex, according to a cyclic process and at the same speed as that of the speech circuit. It is interconnected with the speech circuit by the equivalent of 3 multiplex highways or 72 channels. Of these 48 channels are used for handling digital information and 24 channels are used for voice frequencies concerned with maintenance, operators' sets, and conference circuits.

The exchange of orders and information between the control circuit and the local junctors is made when the synchronizing channels are connected to the highways, during which no information is processed in the junctors.

The control circuit is made up mainly of two logic units, the input-output logic that processes supervision operations for the different channels and calls on the general logic as soon as a significant change is observed, and the general logic that processes in a multiplex way the various problems that are presented to it. A 72-line memory of 24 binary digits is associated with these two logic units.

5.3.4 *Semipermanent Memory*

A semipermanent memory contains all the information concerning the subscribers' lines, the translations and programs of the logic units of the control circuit, and the maintenance.

5.3.5 *Maintenance*

Maintenance uses two distinct types of operation, automatic and manual.

Automatic operation permits the display of the subscribers to be put in or withdrawn from the false-call memory, the highways not in service, and the breakdowns resulting from the tests carried out from the programs written in the semipermanent memory.

Manual operation permits the display of data taken from time slots chosen by the operator

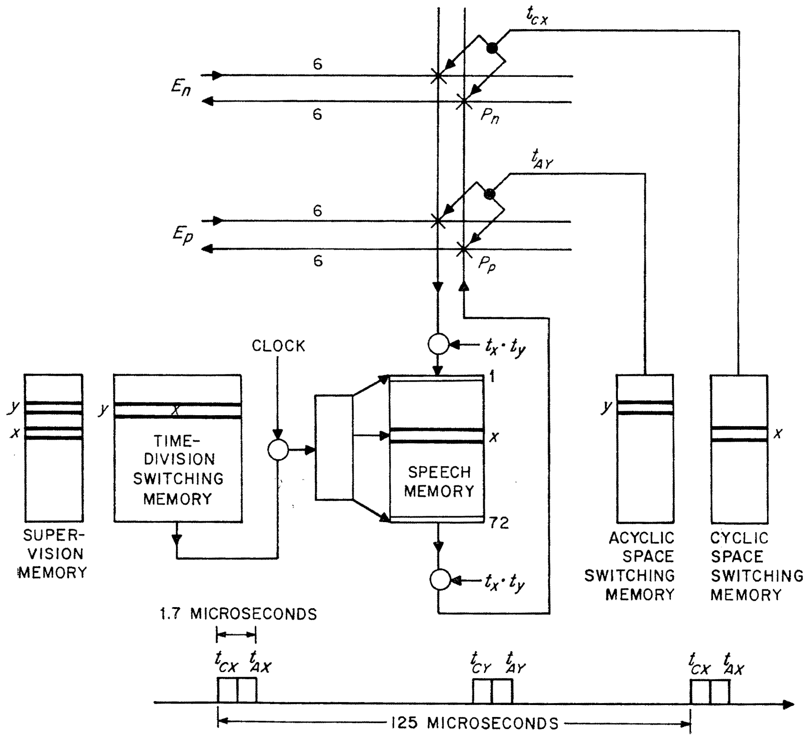

Figure 6—General organization of a local junctor.

at either the input or output of the logic units of the control circuit.

In addition, the maintenance system includes all the control equipments for putting the exchange into service.

6. Supply

The exchanges can be supplied from 220-volt, 50-hertz generating sets or from the mains. In permanent operation part of the supply is duplicated for security reasons.

7. Mechanical Presentation

The main part of the exchange is contained in several identical metal coffers with a weight of about 70 kilograms (155 pounds). The coffers are transportable by hand and can be mounted in racks or stacked directly atop each other (Figures 7 and 8).

Both local and zone exchanges are as identical as possible and differ only in the number of group equipments and in the programs stored in the semipermanent memory.

Each exchange consists of three equipments.

(A) A common equipment providing power supply, control circuit, and semipermanent memory. This equipment is contained in 5 coffers.

(B) A switching unit (a group equipment and a local junctor) contained in 1 coffer. An exchange may have from 1 to 3 switching units giving a maximum capacity of 18 multiplex highways.

(C) A maintenance set and an operator set contained in 2 smaller coffers.

The concentrator consisting of logic, subscribers' line equipment, and supply is contained in a standard coffer.

Figure 7—Front view of metal coffers in which the exchange equipment is mounted.

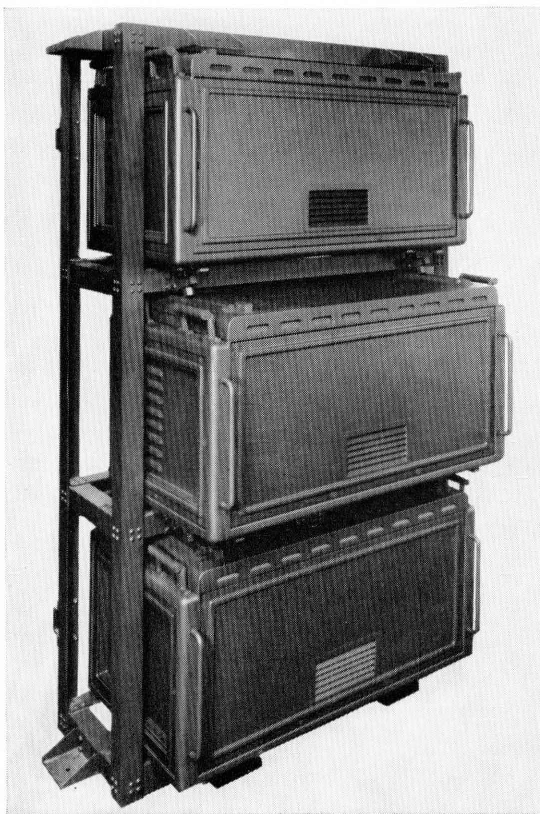

Figure 8—Rear view of coffers holding the exchange equipment.

An exchange can be set up in a shelter transportable on a truck. A local exchange generally uses only 1 switching unit, and 2 concentrators can be added inside the shelter.

8. Conclusion

A tactical network constituted by the units described in this article will have all the characteristics of flexibility and security that are imposed on the transmission services of a modern army.

Four prototypes at present being finished will permit field tests of the equipment as well as of the method of automatic call routing. For this purpose, simulators permitting a complicated network to be represented are included in the prototypes.

The volume and the energy consumption of the equipments using discrete components and semiconductors shows an enormous gain with respect to exchanges of the electromechanical type. They could, however, be reduced even more through miniaturization techniques and especially by integrated circuits.

9. Acknowledgment

It should moreover be noted that the work that ended in the definition and construction of these equipments was successfully conducted through close collaboration between Laboratoire Central de Télécommunications and the Section d'Études et de Fabrications des Télécommunications of the Direction Technique des Armements Terrestres.

Work in progress at the present time will permit this network to be extended to mobile subscribers linked by radio to the fixed units of the network. These subscribers will then have all the advantages of the fixed subscribers.

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Jean Le Corre was born on 24 August 1927 in Guiler-sur-Goyen, France. He obtained the radio engineer's diploma of the École Supérieure d'Électricité de Paris in 1950.

From 1951 to 1954, he held the position of research engineer at the Office National d'Études et Recherches Aéronautiques. He then joined the Laboratoire Central de Télécommunications, where he worked on electronic telephone switching and became Assistant Head of the Telephony Department.

Mr. Le Corre is a member of the Société Française des Électroniciens.

Alfred Pirotte was born on 2 October 1926 in Paris. He obtained the "Licence ès Sciences" from the Faculté des Sciences of Paris in 1955. He then entered the Laboratoire Central de Télécommunications where he worked on autocoherent radars; on electronic switching, notably the construction of the automatic equipment shown at the Brussels exhibition; and on automatic switching equipment using pulse code modulation for the French Army.

Mr. Pirotte is at present Head of the Section on Application of Electronic Switching to Military Equipment.

Etching of Edouard Branly

The International Telecommunication Union has announced another in its series of etchings of eminent personalities in the field of telecommunications. It honors Edouard Branly.

Edouard Branly was born at Amiens, France, in 1844 and died in Paris in 1940. After studying at the École Normale Supérieure he served as a professor at Bourges College and later as co-director of the physics laboratory until 1875. He obtained his doctorate in science in 1873.

In 1875 he became a professor at Rollin College and later professor of physics at the Catholic Institute in Paris. In 1882 he passed his thesis for a doctorate in medicine.

Dr. Branly became well known for his research work on electric discharges, ultraviolet rays, gases, and incandescent bodies. He invented the coherer, which was given his name and was one of the earliest detectors of radio waves. In 1905 in applying this discovery he produced a general solution to the problem of wireless communications.

Besides publishing in scientific magazines, he produced three books in 1895: Basic Treatise on Electricity, Basic Treatise on Physics, and Elementary Course in Physics.

In 1903 he shared the Osiris Prize with Pierre Curie. He was elected a member of the Académie des Sciences in 1911.

This series of etchings was started in 1935. They are on a good grade of paper and measure 23 by 17 centimeters (9 by 6.6 inches) including margins. They are available at 7 Swiss francs each, postpaid, from the General Secretariat, International Telecommunication Union, Place des Nations 1211, Geneva 20, Switzerland.

The eminent persons honored by etchings include: Ampère, Appleton, Armstrong, Baudot, Bell, Branly, de Forest, Edison, Erlang, Faraday, Ferrié, Fresnel, Gauss and Weber, Heaviside, Hertz, Hughes, Kelvin, Kirchhoff, Lodge, Lorentz, Marconi, Maxwell, Morse, Popov, Poulsen, Pupin, Rayleigh, Siemens, Sommerfeld, Tesla, Van der Pol, and Von Karman.

Elements for a General Theory of Service Processes

Application of Characteristic Functionals in Traffic Theory

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Editorial Note: This paper, a summary of which appears below, was presented at the 5th International Teletraffic Congress, which was held in New York, New York, on 14–20 June 1967. Copies of the full paper in French or in English are available on request.

A service system Σ can be considered as a device that transforms an input $x(t)$ (the flow of calls, for instance) into an output $y(t)$ (the flow of served calls, for instance), let us say: $y(t) = \mathcal{T}[x(t)]$; usually

- $x(t)$ and $y(t)$ are stochastic processes
- $\mathcal{T}$ is a nonlinear transformation
- $\mathcal{T}$ is a stochastic transformation (because the holding time is random, for instance).

The mathematical study of Σ, particularly the determination of the probability law of $y(t)$, given the probability laws of $[\mathcal{T}, x(t)]$, can be performed explicitly only in some particular cases; a basic case is the one where $x(t)$ is a Poisson process. But in many cases, $x(t)$, the input for Σ, is the output of another service system Σ' and the Poisson assumption is not good. For considering multistage systems, networks on the whole, et cetera, there is a need for a theory applicable to any input $x(t)$.

With an arbitrary input $x(t)$, there is no chance of getting complete and rigorous equations; but we can succeed in building systematic approximation methods. A first success in this way is the results obtained by Kingman and others for waiting problems; in this case, the approximation is based on the assumption that the traffic offered is close to the congestion value. In case of lost-call systems, the approximation could be based on the assumption that the loss probability is small.

For developing such a theory, a useful tool could be the representation of the probability law of a stochastic process $x(t)$ by its characteristic functional $\varphi(f)$; $\mathfrak{F}$ being a conveniently chosen vectorial space of functions f to t, $\varphi(f)$ is defined as a function of f in $\mathfrak{F}$, by

$$\varphi(f) = E \exp [i \int f(t) x(t) dt]$$

where

$$E = \text{mathematical expectation.}$$

Usually the functions f are taken as positive real functions; it may be useful in some occasions to admit random complex functions f.

The relation $y(t) = \mathcal{T}[x(t)]$ can be expressed by the fact that the characteristic functional ψ of $y(t)$ is a determined function T of φ. The problem is to find an approximation method for computing $\psi = T(\varphi)$. The application to simple cases seems promising.

Teletraffic Engineering Manual

This book was originally published in German under the title "Projektierungsunterlagen für Vermittlungssysteme" and is now available in English. Following an introduction and explanatory material are detailed tabulations and diagrams basic to the design of telephone and teleprinter switching systems.

Measuring 11 by 15 centimeters (4.4 by 5.9 inches) the book may be obtained from Standard Elektrik Lorenz, 42 Hellmuth-Hirth-Strasse, 7000 Stuttgart-Zuffenhausen, Federal Republic of Germany, at DM 8 per copy.

Entraide Networks Combined with Link Systems *

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1. Introduction

The design of all modern switching systems is based on multistage link operation. As the aim is to minimize the cost of equipment for a required grade of service, a compromise is found among many others between the matrix sizes and the number of stages. It is known that for networks in which all paths have the same length, the smaller the matrix the larger the number of stages, but this is evidently limited by the amount of control required.

It is also well known that the minimum cost of a switching network varies little with matrix size, so that manufacturing standardization usually favors adoption of only a few sizes. The manufacturing economy of limited matrix sizes and the flexibility introduced by the concept of entraide permit the development of new networks in which all paths are not of the same length.

A link system with entraide is defined as a system in which some outlets from a given connecting stage are connected to inlets of the same or a preceding stage. Thus calls may traverse a given stage more than once. Usually, such longer paths are last-choice paths. The terms "mutual aid," "re-entering overflow," and "reciprocal overflow" have also been used in the rather scarce literature on this subject. As proposed to the Nomenclature Committee of this Congress, the short term "entraide" is preferred.

2. Geometry of an Entraide Network

2.1 Purpose

The description that follows is related to a particular design. Figure 1 represents the entraide network between K sections or matrices, whatever be the stage of the link system they pertain to. Each of these matrices has r inlets from the preceding stage and s outlets to the next stage, plus t entraide outlets and n entraide inlets, respectively, to and from the other $(K-1)$ matrices of the same stage. We shall only consider here the case $n < e \leq t$ defining e as equal to the minimum of $[t, (K-1)n]$, so that each of the Kn entraide inlets is multipled over an average number $i = e/n$ of the outlets, in fact taken only among $(K-1)e$ of them. For i being a whole number > 1, this may be considered as the homogeneous grading of Kn devices with availability e. If i is fractional, we have a pseudo-homogeneous grading with the two interconnection numbers $i_1 < i < i_2 = i_1 + 1$.

Such an entraide network is then defined by the parameters K, e, n, from which can be derived the average number f' of entraide links between any two sections.

$$f' = \text{minimum}\left[n, \frac{e}{K-1}\right]. \tag{1}$$

It is to be noted that, when f' is not a whole number, the $K(K-1)$ groups of such unidirectional links can be divided in K_1 groups of f_1' links and K_2 groups of $f_2' = f_1' + 1$ links, with

$$\left.\begin{aligned} K_1 + K_2 &= K(K-1) \\ K_1 f_1' + K_2 f_2' &= Ke. \end{aligned}\right\} \tag{2}$$

The generalization is applicable to bidirectional entraide links but will not be considered here.

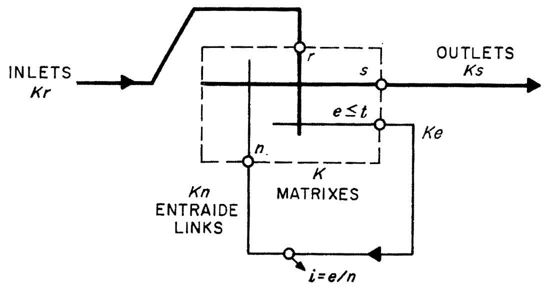

Figure 1—Entraide network.

* Presented at 5th International Teletraffic Congress, New York, New York; 14–20 June 1967.

2.2 Description of a Particular Case

Approximate calculations can be made from the preceding information, but a more-precise description is needed for traffic simulation. Figure 2 is for a case where $K = 7$ matrices numbered from 0 to 6, and $n = 4$. The entraide links may be numbered from 0 to 3 within each matrix, but we have considered that it is easier for addressing a computer memory to number all of them from 1 to Kn, here from 1 to 28, starting from those of matrix 0. Finally the entraide outlets are numbered from 1 to 12 within each matrix ($t = 12$).

We have adopted here the usual drawing conventions for homogeneous gradings: on a grid of $(K - 1)e = 6 \times 12 = 72$ points, some of them have been joined in groups of three, because here $e =$ minimum $[12, (K - 1)n]$ $= 12$, so that the interconnecting number is $i = e/n = 12/4 = 3$. It is explained on the right-hand part of the figure why it is valid for any one of the K matrices, because of the cyclical rule applied.

A horizontal cut on this figure shows the number, $f' = e/(K - 1) = 2$, of entraide links between any matrix and any of the others $(K - 1)$.

The link 15 marked on Figure 2 is one of the two links from matrix 0 to matrix 3; it uses outlet 9 of matrix 0 and inlet 2 of matrix 3; it is commoned also with outlet 8 of matrix 1 and outlet 7 of matrix 2.

2.3 Hunting Rules

The entraide network so far described is used only to build paths through the whole link system when shorter paths are not available, that is, when none of the s outlets of a matrix may serve to build a free path together with one of the r inlets of the same matrix. Such a case would lead to blocking without entraide; it is fairly possible that a path may be built through the entraide network from a usable inlet to a usable outlet in another matrix.

We have then one stage more in the conditional

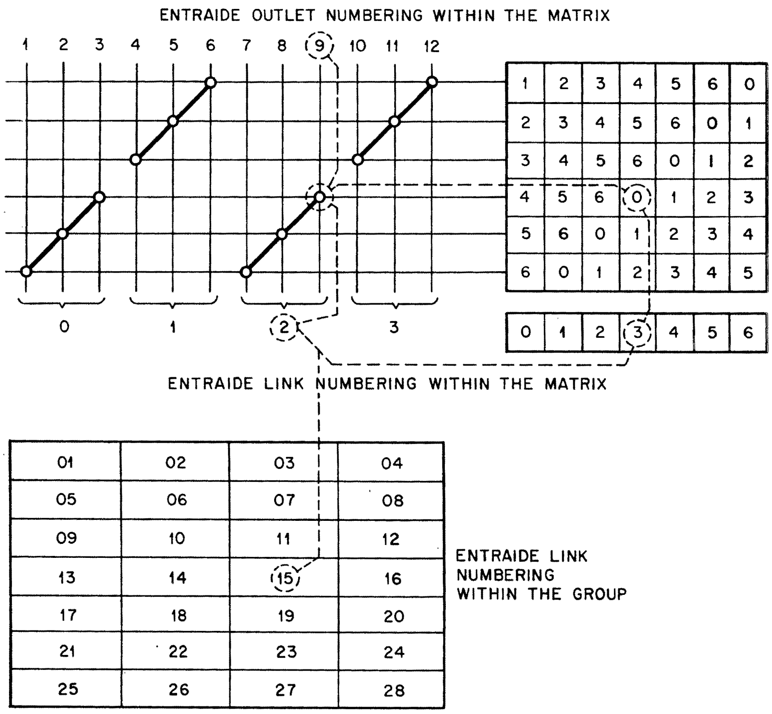

Figure 2—Entraide network details showing cyclical permutation.

selection process, this stage being loaded by only a part of the total traffic.

Let us consider a call that has reached one of the inlets in a defined matrix but for which the only usable outlets are within some, maybe all, of the other matrices $(K - 1)$. The path hunting rule through the entraide stage is sequential *without* home position among all the matrices $(K - 1)$ having both usable outlets and free entraide links from the calling matrix, then again sequential *with* home position among those free matrices out of the f' so defined.

As traffic simulations are easier to program by applying the exact hunting rules existing in the actual circuits, we have also reversed the hunting direction at each call attempt, the starting point being chosen at random.

From this hunting rule, it can be expected that the busy-hour operation of this homogeneous grading is not far from the assumption of random hunting, that is, this set of entraide links may be considered as a symmetrical traffic group in the precise sense given by Fortet and Canceill [1].

Table 1 shows all entraide links available from each calling matrix for the case presented geometrically in Figure 2. As stated the hunting rule is from a random starting point so that each line is to be considered cyclical or repeated modulo 12. Hunting direction is from left to right for even-numbered calls and from right to left for odd-numbered calls.

2.4 Mean Availability

The concept of equivalent availability received attention in Germany some years ago, where Bininda and Wendt [2] proposed it for single-stage gradings and 2-stage link systems. Kharkevich [3] and Lotze [4] have also devoted some effort to this subject, but the present state of the art shows in some cases marked differences between equivalent availability and the mean value of a variable availability.

Nevertheless we present here shortly the calculation of mean availability for the entraide network so far described.

If each of the K matrices has s "direct" outlets, the variable availability $k'(d)$ from a given calling matrix to the Ks outlets of the group is a number between s and Ks, which depends mainly on the traffic load d of the entraide links. Following Le Gall's lemma [5], we calculate it first assuming Bernoulli distribution on entraide links.

Let us call P_k the probability that k determined matrices out of the $(K - 1)$ are

TABLE 1
Entraide Links Available from Each Calling Matrix

Calling Matrix	Entraide Links											
0	05	07	09	11	13	15	18	20	22	24	26	28
1	09	11	13	15	17	19	22	24	26	28	02	04
2	13	15	17	19	21	23	26	28	02	04	06	08
3	17	19	21	23	25	27	02	04	06	08	10	12
4	21	23	25	27	01	03	06	08	10	12	14	16
5	25	27	01	03	05	07	10	12	14	16	18	20
6	01	03	05	07	09	11	14	16	18	20	22	24

available through an entraide network and the others $(K-1-k)$ are not available. Then

$$k'(d) = Ks - (K-1)s \sum_{k=1}^{K-1} C_{K-2}^{k-1} P_k \quad (3)$$

with

$$P_k = (d^{f'})^k (1 - d^{f'})^{K-1-k}. \quad (4)$$

Expanding P_k and replacing d^x by the probability of x determined entraide links being busy in the symmetrical traffic group of Kn devices, denoted, that is

$$[p^x]^D{}_{Kn}$$

with $D = Knd$, we have

$$k' = Ks - (K-1)s \cdot A \quad (5)$$

$$A = \sum\sum_{i,j=0}^{i+j \leq K-2} C^j{}_{K-2} C^i{}_{K-2-j} \times (-1)^i [p^{f'(i+j+1)}]^D{}_{Kn}. \quad (6)$$

It is easily shown that only the term $i + j = 0$ is different from zero, so that

$$k' = s\{K - (K-1)[p^{f'}]^D{}_{Kn}\}. \quad (7)$$

This equation reads for entraide traffic with Bernoulli distribution

$$k'(d) = s[K - (K-1)d^{f'}] \quad (8)$$

and for entraide traffic with Erlang distribution

$$k'(D) = s\left[K - (K-1)\frac{E_{Kn}(D)}{E_{Kn-f'}(D)}\right]. \quad (9)$$

This result shows that if entraide traffic is maintained within certain limits, that is, with $[p^{f'}]$ low enough, the availability from one calling matrix to all the outlets of the group is nearer to Ks than to s, its value measuring in some degree the permeability of the entraide network.

3. Approximate Dimensioning Methods

3.1 Principles

Up to now, all approximate dimensioning methods for multistage link systems rely on the assumption of stochastic independence between successive stages. The principle of this method may be conveniently associated with the names of Jacobaeus [6], Lee [7], and Le Gall [5], the latter having clearly shown the distinction between the geometric and the stochastic parameters.

When applied to entraide networks, this method implies the following steps.

(**A**) Construct a graph of possible paths not using entraide links.

(**B**) Derive the entraide traffic offered to each entraide network.

(**C**) Construct a graph of all possible paths that *do* or *do not* use entraide links.

(**D**) Derive the final blocking.

For points (**B**) and (**D**) intelligent guesses have to be made concerning the traffic distribution at each stage.

In a recent paper, Grandjean and Chastang [8] have studied isolated entraide networks by solving the equations of state, but obviously this method cannot be generalized to multistage link systems including entraide because of the size of the linear system to be solved. Their results then apply only to entraide networks associated with single-stage systems. When entraide networks associated with 2-stage (or more) link systems are considered, calculation of entraide traffic is of a different nature; this traffic may be considered as that refused by a link system instead of a full-availability group, and it is known that internal blocking, or matching loss, arises for a large number of combinations of busy devices within the successive stages. This is why a description of only the mean entraide traffic may be considered as a better approximation than if it derived from full occupancy of full-availability groups.

Thus, in the following approximate calculations, we will consider Erlang traffic distribution in the symmetrical entraide traffic group. No better justification can be given than comparison of calculated results with simulated results, which is given in Section 4.

3.2 Entraide Networks with a 2-Stage Link System

This example has been taken from a crossbar system because it is well known as is the terminology used. Figure 3 represents the grouping of $g = 4$ group selection units serving jointly a number of routes of $N_i = mh_i$ trunks each and a total traffic ΣT_i. It is clearly shown that the outlets of the 4 group units are multipled, so that $\Sigma_i N_i \leq 1040 = 20 \times 52$.

Each group unit has $m = 20$ secondary sections of 52 outlets and $fK = 14$ inlets (secondary selectors), and $K = 7$ primary sections with 40 inlets (primary selectors), 40 direct links and 12 entraide outlets, and $n = 4$ entraide inlets (primary entraide selectors).

Figure 4 shows the graph of the paths available for a call intended for a given route. The mf direct links available from the calling section have been drawn with dotted lines, and the remaining $(K - 1)mf$ direct links in solid lines.

3.2.1 *Calculation of Entraide Traffic*

Classical equations for a 2-stage link system give the time congestion without entraide with

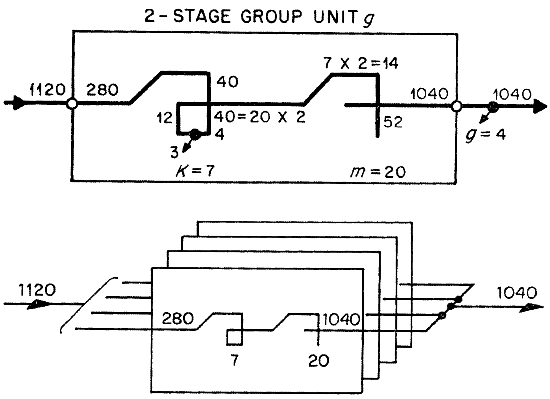

Figure 3—Representation of $g = 4$ group units, each of 2 stages plus entraide.

Erlang distribution on the route and Bernoulli distribution on the mf direct links (out of total Kmf, or even $gKmf$ for proper distribution of incoming routes over the gK primary sections).

$$P_1 = \sum_{j=0}^{m} C_m{}^j (p_1{}^f)^{m-j} \times (1 - p_1{}^f)^j \frac{E_{mh_i}(T_i)}{E_{(m-j)h_i}(T_i)} \quad (10)$$

$$p_1 = \frac{\sum T_i}{gKmf} \quad (11)$$

offered load per direct link.

This equation reduces for $h_i \leq 1$ to Jacobaeus' equation

$$P_1 = E_{mh_i}(T_i)/E_{mh_i}(T_i/p_1{}^f) \quad (12)$$

which may be considered as a good approximation of (10) for values of h_i greater but not much greater than unity.

The total traffic gD offered to the g entraide networks will then be calculated (full occupancy of the outgoing group causes immediate rejection of the call, or second attempt, or alternative routing) through the equation

$$gD = \sum_i T_i E_{mh_i}(T_i) \times [-1 + 1/E_{mh_i}(T_i/p_1{}^f)]. \quad (13)$$

Considering that this total traffic is equally distributed over the g entraide networks, we have D erlangs offered to the Kn entraide selectors of each unit.

3.2.2 *Calculation of Blocking*

Using Figure 4, the blocking towards route i is easily derived with the following equation for a 3-stage link system completely interleaved.

$$P_i = \sum_{k=0}^{K-1} Q_k P_{k+1,i} \quad (14)$$

where Q_k is the distribution of the number k of primary sections available through the entraide network and $P_{k+1,i}$ is the blocking of the 2-stage link system constituted by route i and the $(k+1)mf$ links to which access is given by the calling section and the other k primary sections considered. Then

$$Q_k = C_{K-1}{}^k \sum_{\lambda=0}^{k} C_k{}^\lambda (-1)^{k-\lambda} \frac{E_{Kn}(D)}{E_{Kn-e+\lambda f'}(D)} \quad (15)$$

$$P_{k+1,i} = E_{mh_i}(T_i)/E_{mh_i}(T_i/p_1{}^{(k+1)f}). \quad (16)$$

Strictly speaking, the equation used for $P_{k+1,i}$ is only approximate because, for values of the summation index k near to $K-1$, the distribution to be applied to the links is nearer to Erlang than to Bernoulli. Nevertheless, the small error then occurring is to be weighted by the corresponding Q_k, which are usually small.

By providing a sufficient number of entraide selectors Kn for traffic D, it is possible to maintain P_i very near to $P_{K,i}$ (blocking if entraide were perfect), which is nearly equal to the full-availability loss $E_{mh_i}(T_i)$ for $p_1 \leq 0.72$.

A practical method will then be to dimension the routes according to the full-availability Erlang equation and determine the resulting internal blocking as the difference $[P_i - E_{mh_i}(T_i)]$ may be less than the required value, for instance 0.001 or 0.005, by providing the necessary number of entraide selectors per group unit. The validity of this method may be assessed by comparing the values of internal blocking calculated with the results of traffic simulations.

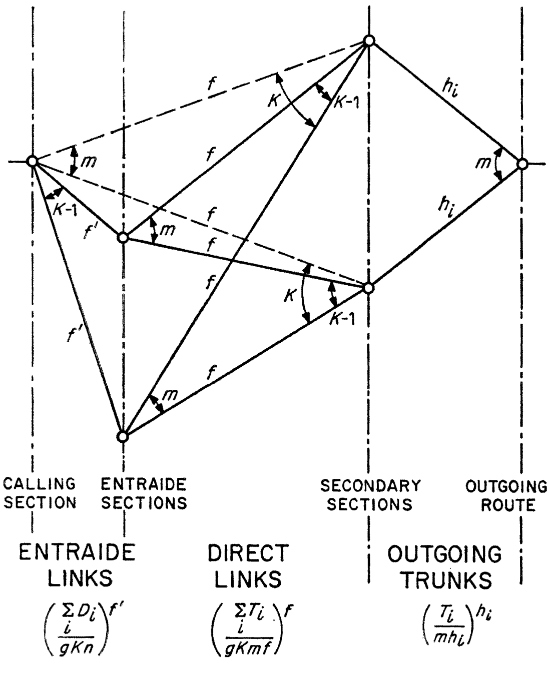

Figure 4—Paths available for a call.

3.2.3 *Simplified Calculations*

In most of the practical cases, the number of entraide selectors is provided for an average entraide link load of $0.25 < d < 0.50$ erlang. When this is the case, the calculation of (15) and (16) is greatly simplified by the use of Table 2 due to Chastang [9], giving the correction factor ϵ to be applied to P_K, the loss if the entraide were perfect.

$$P \cong (1+\epsilon)P_K. \quad (17)$$

It has been found that ϵ depends mainly on K and $d^{f'}$ (of entraide links) but much less on p_1 and on the load of the outlets. Then Table 2 has been calculated "on the safe side," for low C and high p_1, and is of real help for practical dimensioning of various group units.

Approximate equations for ϵ are

$$\epsilon \cong (K-1)\left(\frac{P_{K-1}}{P_K} - 1\right)d^{f'},\ d < 0.35 \quad (18)$$

$$\epsilon \cong \frac{K-1}{2}\left(\frac{P_{K-2}}{P_K} - 1\right)d^{f'},\ d < 0.50. \quad (19)$$

For $d > 0.50$ (that is, in the practical range of K and f' values when $1-(K-2)\ d^{f'}$ is significantly different from zero) these equations cannot be guaranteed to give results on the safe side, and calculation of (15) and (16) is needed for all K values.

4. Traffic Simulation

4.1 Model and Assumptions

The model used is known as the "roulette" of Kosten, simulating actually the time-independent Markov process of the successive states of the network by generating independent call attempts and call releases. The result is an unbiased estimation of the call congestion.

Only Erlang type traffic has been considered here, that is, constant probability of a new call attempt, though Engset and Bernoulli type traffic could have been generated easily, because the inlets of the network studied here cannot be considered as primary traffic sources. As we did not want to make any restrictive assumption concerning the size of incoming traffic routes and their actual cabling on the inlets of the group units, we have applied the following rule of allocation of call attempts to inlets: to choose at random one starting point among all the inlets, then to allocate this call to the first free inlet by sequential hunting from this starting point. It is then found that a call attempt will always be placed on one inlet, unless all inlets of the network be simultaneously occupied.

Such an assumption is rather conservative and is likely to give blockings on the safe side, because in actual operation of exchanges, the traffic offered to such a network has always been somewhat smoothed by the preceding stages. We think nevertheless it is better to perform intrinsic study of the group units considered by offering them pure Erlang traffic. Any simulation generating Bernoulli distributed traffic on the groups of inlets of each matrix is likely to give lower blockings than the actual ones.

4.2 Pseudo–Random Number Generator

A series of random numbers uniformly distributed is needed for these simulations, as well as for event generation, for allocating calls to inlets and calls to routes, for choosing starting points of sequential hunting rules, and for choosing the path to be released. We have used independent series of 32-bit pseudo-random numbers, generated through a congruent multiplication method. The starting number and, more important, the multiplier have been chosen after extensive statistical tests including correlation tests.

4.3 Number of Calls Simulated and Statistical Confidence

All simulations start from unoccupied state, so that a number of calls have to be placed and released before reaching statistical equilibrium. This transition increases with the size of the network to be simulated, in fact with

TABLE 2

Correction Factors ϵ

K	7	6				5				4		
f	2	14/6		2		14/5		2		14/4		2
$d \backslash f'$	2	12/5	2	12/5	2	3	2	3	2	4	3	2
0.225	0.03	0.02	0.03	0.03	0.04	0.005	0.03	0.01	0.035	0.0	0.01	0.03
0.250	0.035	0.02	0.035	0.03	0.05	0.01	0.03	0.015	0.04	0.0	0.01	0.04
0.275	0.04	0.025	0.045	0.035	0.065	0.01	0.04	0.015	0.055	0.0	0.015	0.045
0.300	0.05	0.03	0.055	0.04	0.08	0.01	0.05	0.02	0.07	0.005	0.015	0.06
0.325	0.06	0.035	0.065	0.05	0.095	0.015	0.065	0.025	0.09	0.005	0.02	0.07
0.350	0.075	0.05	0.08	0.065	0.11	0.025	0.085	0.035	0.12	0.01	0.03	0.09
0.375	0.09	0.065	0.10	0.08	0.13	0.035	0.11	0.05	0.14	0.015	0.04	0.11
0.400	0.11	0.085	0.12	0.10	0.15	0.05	0.13	0.07	0.17	0.02	0.06	0.15
0.425	0.13	0.11	0.15	0.13	0.18	0.07	0.17	0.09	0.21	0.035	0.085	0.20
0.450	0.16	0.13	0.18	0.16	0.22	0.10	0.21	0.12	0.26	0.05	0.12	0.26
0.475	0.19	0.16	0.22	0.19	0.26	0.13	0.26	0.15	0.32	0.07	0.15	0.33
0.500	0.23	0.19	0.26	0.23	0.31	0.16	0.32	0.19	0.38	0.10	0.21	0.41

the total intensity of traffic simulated. In the examples described, we have arbitrarily limited it to 10 000 call attempts before starting to count blocked calls.

Statistical confidence is estimated through use of Student's t distribution. For a number n of samples of 5000 calls each, an unbiased estimation of the variance σ^2 of the loss probability B is calculated from the sample variance $\bar{\sigma}^2$.

$$\sigma^2 = \frac{n}{n-1}\,\bar{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(B_i - \bar{B})^2 \quad (20)$$

$$\bar{B} = \frac{1}{n}\sum_{i=1}^{n} B_i. \quad (21)$$

Then, at a 95-percent confidence level, the true value B falls in the following confidence interval $\bar{B} \pm \Delta B$ with

$$\Delta B = \frac{\sigma}{n^{1/2}}\, t_{0.95,n}. \quad (22)$$

Practically, the value of $t_{0.95,n}$ is near to 2 when n is greater than 10, that is, for more than 50 000 call attempts.

To shorten the simulations, all routes have been taken equal within one experiment, thus allowing averaging of the number of lost calls to each route. Routes of 20, 40, and 80 trunks have been considered (h = 1, 2, and 4).

4.4 Results

We have selected the following set of simulations because they present some aspects of the blocking behavior against different parameters.

In Table 3, $g = 4$ group units are fully loaded for serving 1040 trunks. It can be seen that the Erlang loss of the routes is fairly high, which explains the high values of calculated entraide traffic. Nevertheless, in such cases, the measured entraide traffic is smaller. For Erlang losses of the routes in the range of 0.01, both calculated entraide traffic and total loss approximate rather well the values obtained by simulation. For smaller Erlang losses, the calculated entraide traffic is smaller than the measured traffic, but the total blocking is kept very near to the Erlang loss of the routes, so that the error does not influence practically the value of the internal blocking, that is, the difference $P - P_E$, or $(1+\epsilon)P_K - E$.

We remark also that, for the higher loads, P_E is less than E, which means that Erlang distribution is distorted on each route, this effect

TABLE 3

Simulation Results for $g = 4$ Group Units Serving 1040 Trunks

Number of Routes R and Sizes mh	52 Routes of 20 Trunks				26 Routes of 40 Trunks			13 Routes of 80 Trunks		
Data										
Traffic per link p_1	0.78	0.75	0.72	0.68	0.78	0.75	0.72	0.78	0.75	0.72
Total traffic RT	873.6	840.0	806.4	761.6	873.6	840.0	806.4	873.6	840.0	806.4
Traffic per route T	16.80	16.15	15.51	14.65	33.60	32.31	31.02	67.20	64.62	62.04
Simulation Results										
Number of attempts C_1	120 000	100 000	100 000	100 000	120 000	100 000	100 000	280 000	140 000	160 000
Route loss P_E	0.0659	0.0584	0.0515	0.0394	0.0321	0.0262	0.0195	0.0130	0.0076	0.0043
Total loss P	0.0917	0.0741	0.0588	0.0414	0.0466	0.0328	0.0215	0.0172	0.0089	0.0047
± Confidence interval	±0.0046	±0.0053	±0.0039	±0.0034	±0.0041	±0.0040	±0.0024	±0.0017	±0.0017	±0.0009
Entraide rate C_M/C_1	0.1180	0.1005	0.0828	0.0606	0.0929	0.0711	0.0514	0.0588	0.0384	0.0233
Entraide traffic (total)	103.1	84.5	66.7	46.2	78.1	59.7	41.4	51.4	32.3	18.8
Calculations										
Erlang loss $E = E_{mh}(T)$	0.0814	0.0674	0.0547	0.0397	0.0402	0.0291	0.0201	0.0150	0.0083	0.0042
Loss if perfect entraide P_K	0.0844	0.0688	0.0555	0.0399	0.0417	0.0297	0.0204	0.0156	0.0085	0.0043
Total loss $(1+\epsilon)P_K$	0.1802*	0.1100*	0.0636*	0.0401	0.0590*	0.0365	0.0214	0.0168	0.0086	0.0043
Entraide rate $(P_1 - E)$	0.1615	0.1213	0.0896	0.0571	0.1019	0.0667	0.0416	0.0458	0.0228	0.0103
Entraide traffic (total)	141.1	101.9	72.3	43.5	89.0	56.0	33.6	40.0	19.2	8.3

* This value has been calculated through (15) and (16) because calculated entraide traffic is too high to allow use of approximate equations.

being probably due to interdependence of the stage of links and of the stage of outlets.

In Table 4, the number of routes has been taken smaller than the maximum possible to focus the attention in the range of Erlang losses near to 0.01. Here again, the approximate calculation methods give rather good approximation of total blocking, a little on the low side, but precise enough for engineering use. Though the entraide traffic is always underestimated by the approximate calculations, we suppose that the favorable effect of interdependence compensates rather well for the error made on calculated entraide traffic.

Last of all, these simulations show that in case of overload the interdependence effect becomes more important, so that degradation of the grade of service can be expected to be less pronounced than was forecast.

We think this phenomenon applies generally to all multistage link systems; unfortunately, up to now it has proved rather difficult to take it into account in approximate dimensioning methods except for very simple 2-stage link systems.

4.5 Confidence Intervals

Some simulations have been performed for a much larger number C_1 of call attempts to get some insight into the convergence process. It is found that the confidence interval decreases very slowly, though the measured value is rather equal to the theoretical value. It may then be guessed that the calculation of this interval for a confidence of 95 percent, through use of Student's t distribution, is rather conservative. Confidence levels of 90 percent or 80 percent could be visualized, or a narrower law than Student's t chosen.

4.6 Contagious Process

A priori the principle of re-entering traffic on a given stage through such an additional entraide stage may be considered dangerous; some constantly increasing or contagious blocking process may be feared and this is why the entraide has been practically applied to only a small amount of the total traffic, say, less than 10 percent.

However, the partial results presented here do

TABLE 4

Simulation Results for $g = 3$ Group Units Serving Fewer Than 1040 Trunks

Size of Routes mh	20 Trunks			40 Trunks			80 Trunks	
Number of Routes R	52	51	48	23	22	21	11	10
Data								
Traffic per link p_1	0.75	0.72	0.68	0.78	0.75	0.72	0.78	0.72
Total traffic RT	630.0	604.8	571.2	655.2	630.0	604.8	655.2	604.8
Traffic per route T	12.12	11.86	11.90	28.49	28.64	28.80	59.56	60.48
Simulation Results								
Number of attempts C_1	100 000	100 000	100 000	140 000	100 000	100 000	330 000	240 000
Route loss P_E	0.0094	0.0091	0.0091	0.0069	0.0077	0.0093	0.0019	0.0026
Total loss P	0.0121	0.0100	0.0094	0.0112	0.0091	0.0098	0.0030	0.0028
$\pm$ Confidence interval	$\pm$0.0016	$\pm$0.0012	$\pm$0.0009	$\pm$0.0022	$\pm$0.0014	$\pm$0.0012	$\pm$0.0006	$\pm$0.0005
Entraide rate C_M/C_1	0.0562	0.0432	0.0305	0.0555	0.0431	0.0344	0.0331	0.0165
Entraide traffic (total)	35.4	26.1	17.4	36.4	27.2	20.8	21.7	10.0
Calculations								
Erlang loss $E = E_{mh}(T)$	0.0106	0.0089	0.0091	0.0081	0.0087	0.0093	0.0021	0.0026
Loss if perfect entraide P_K	0.0109	0.0091	0.0092	0.0085	0.0089	0.0094	0.0022	0.0027
Total loss $(1+\epsilon)P_K$	0.0115	0.0094	0.0093	0.0091	0.0092	0.0095	0.0022	0.0028
Entraide rate $(P_1 - E)$	0.0432	0.0296	0.0217	0.0388	0.0311	0.0265	0.0125	0.0068
Entraide traffic (total)	27.2	17.9	12.4	25.4	19.6	16.0	8.2	4.1

not show such contagious behavior: It seems as if the interstage dependence acted as a good "antibiotic!" It is then possible that design engineers have been too timid in applying this principle, and that larger use of entraide in presently designed electronic switching systems may prove feasible and may produce crosspoint savings. This will be the subject of later studies.

5. Conclusion

The practical dimensioning of entraide networks combined with link systems has been shown possible through an approximate calculation method. The precision of such methods was not expected to be very good, because the errors made in calculating entraide traffic react as a multiplying factor on the calculation of final blocking.

Nevertheless we have shown that there was some compensation for the error stemming from the mandatory independence assumption, so that fortunately the method gave reliable results in a fairly good range for practical application.

Similar results have been obtained by Le Gall and Basset [10] in a study dealing with special reinforced entraide arrangements designed for large exchanges. Not only are the approach and the results similar, but the assumptions underlying the simulations are the same as those pointed out in Section 4.1; particularly the inlets are not primary traffic sources so that the probability of a new call attempt must not be made independent of the instantaneous level of occupation in the group.

We hope this modest contribution will serve as a basis for more-extended studies, as well as for theoretical work covering large families of networks. It is particularly necessary to emphasize the role of those parameters that determine the design of such systems.

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Einheiten in Physik und Technik (Units in Physics and Engineering)

This is the third edition of the Standard Elektrik Lorenz handbook prepared under the direction of Dr. A. Sacklowski. Alphabetically listed are all important units and dimensional relations of physical and technical quantities, together with conversion factors and explanations.

The latest units have been added to this edition, and a careful review has been made of national and international standards and of changes resulting from recent progress in natural science and engineering.

The book has a plastic cover over its 268 pages, which are 11 by 17 centimeters (4.4 by 6.7 inches). It can be obtained for DM 19 from Deutsche Verlags-Anstalt, Stuttgart, Germany.

Call Routing Strategies in Telecommunication Networks *

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1. Introduction

The telephone systems that are now in operation are, if a few experimental exchanges are excepted, electromechanically controlled and they offer at a reasonable cost relatively limited possibilities as regards call routing. On the contrary, all the modern semielectronic, quasielectronic, or fully electronic telephone systems that are now being analyzed, designed, or developed have electronic control units that are in fact more or less specialized computers. Due to the specific properties of the computers, these systems offer at a low cost a great flexibility [1] for routing calls, both inside the exchange and from one exchange to another. At the expense of a small increase in the size of the memories, strategies can be implemented that are elaborate enough to produce optimal traffic flow—if however we know how to define such an optimum—and satisfactory reliability.

Moreover the International Telegraph and Telephone Consultative Committee (CCITT) has become interested in the handling of intercontinental traffic by what will be defined later as "dynamic" strategies, which take into account the state of occupancy of the different routes available to set up a connection determined by an origin and a destination. Such strategies permit not only an improvement in traffic balancing and in some cases an increase in the amount of traffic handled but also better utilization of an intercontinental network by taking advantage of the noncoincidence of busy hours in different countries [2].

The problem of finding an optimal strategy implies first of all the defining of what may be called an optimality criterion, which will be discussed in Section 4 of this paper. The problem itself can be stated in two different ways.

(A) For a particular existing network and a given traffic pattern, what is the best way of using the network? In other words, how do we maximize (or minimize) a certain function (for instance the total traffic handled) defined by the criterion.

(B) For a given traffic pattern, how do we design an optimal network? In this case, not only an optimal routing strategy must be found but also the optimal configuration of the network.

The second problem is obviously much harder than the first and will not be considered in this paper.

Optimal strategies have been investigated by several authors and namely in a remarkable paper published recently by Benes [3], where a number of heuristic rules are given and several optimality theorems are proved; unfortunately, the results apply only to certain classes of strategies and networks.

(A) The strategy is such that no call is refused when it is possible to route it through the network.

(B) The network is such that all possible paths to route a call have the same length, that is, the same number of links used in tandem.

Consequently, the study of Benes applies mainly to the speech network of an exchange. Our aim in the present paper is to study routing methods in a network interconnecting several exchanges for which the above two points cannot be admitted. This problem has also been studied by several authors and particularly by Weber [4], who showed that the two points in question were closely correlated in the sense that for those networks where the possible paths for routing a given call do not all have the same length, it is better in certain cases to refuse some calls that could be accepted if circuit freedom were considered as a sufficient condition. This conclusion will be emphasized further on in this paper.

After some general considerations on a possible classification of routing strategies and performance criteria, numerical results obtained by artificial traffic simulations on a simple network will be presented, discussed, and compared with the results given by approximate calculations.

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2. Classification of Routing Strategies

2.1 Definitions

Before examining the different possible strategies we shall first give the definition of some terms to be used throughout this paper.

Consider for instance the communication network of Figure 1. A communication network can be represented by a graph the nodes of which are exchanges (for instance telephone exchanges) such as A, B,..., . A branch of the graph, such as AB, BD,..., is a transmission section, that is, the set of circuits connecting exchanges A and B, B and D,..., . Each section can be composed of one group of one-way or both-way circuits or of two groups of one-way circuits, each group being used in the latter case for one direction of transmission. In some cases, not considered here, a section may have two groups of one-way circuits and one group of both-way circuits. An exchange is said to be a tandem exchange if it is provided with the necessary switching equipment to interconnect incoming circuits of one section with outgoing circuits of another section. For example, let us assume that sections AB and BC (Figure 1) are composed of both-way circuits; if a call from exchange A to exchange C can be routed via exchange B, then B is a tandem exchange. The path followed by a call through the network is called a route: a route is therefore composed of one or several sections (more precisely of one or several oriented groups of circuits, if there are no both-way circuits). The length of a route is defined as the number of sections the route is composed of; this is a topological length. When necessary the metric length of a route will denote the sum of the lengths of the different sections of the route (expressed in meters, kilometers, miles,...). An exchange that does not have the tandem feature is a terminal exchange and handles only its own outgoing or incoming calls.

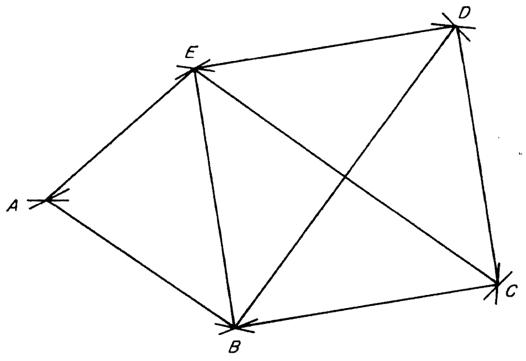

Figure 1—Communication network.

The amount of traffic, expressed in erlangs, that is originated by a particular exchange and destined to another particular exchange is a traffic flow. The set of all traffic flows of a network is the traffic pattern, which can be represented by a square traffic matrix with as many rows and columns as there are exchanges in the network.

In a communication network, there are generally several possibilities for routing a given call, each possibility corresponding to a different route. For instance, in the network of Figure 1, if the circuits are both-way and if exchanges C, D, and E are tandem exchanges, a call from A to B may use one of the following routes.

AB of length 1
$AECB$, $AEDB$ of length 3
$AECDB$, $AEDCB$ of length 4.

As soon as there is more than one possible route to establish some calls, a rule must be applied to choose the route to be assigned to each call. Such a rule will be called a routing strategy (some authors prefer: routing method, routing policy,...).

2.2 Classification

There exists a very large number of possible routing strategies in a communication network; that is why we shall attempt to introduce a classification of routing strategies according to their main characteristics.

2.2.1 *Stochastic Nature*

A routing strategy is probabilistic if the choice of the route involves to some extent a probability distribution. In the above example concerning a call from A to B a probabilistic routing strategy might consist in choosing route AB with probability p_1, route $AECB$ with probability $p_2, \ldots$, route $AEDCB$ with probability p_5 so that $p_1 + p_2 + \ldots + p_5 = 1$, if all 5 routes are available and free.

Strategies which are not probabilistic are deterministic. A particularly important case of deterministic strategies is the sequential strategy where possible routes are hunted in a prescribed order; for each point-to-point relation, a routing table gives a list of the possible routes and the order in which they must be chosen. If the list for a call from A to B is given, in our example, by AB, $AECB$, $AEDB$, $AECDB$, $AEDCB$, the call is routed directly if section AB (group of circuits AB) has at least one free circuit; if not, the call is routed via exchanges E and C if all the three sections involved have at least one circuit free, and so forth.

Sequential strategies are used in the routing method known as "alternate routing" [5].

A trivial particular case of sequential strategies is the direct strategy where each call can use only one route.

2.2.2 *Dependence on Network Occupancy*

A routing strategy where the choice of the route depends on the state of occupancy of the different sections (or one-way groups of circuits) involved in the different possible routes will be designated as a dynamic strategy. If the choice of the route does not depend on this state of occupancy, the strategy is said to be static: for example, the above sequential strategy is static.

An example of dynamic strategy is as follows. Let P_i denote the percentage of busy circuits of the most loaded section (highest percentage of busy circuits) for each possible route. The route chosen will be that having the lowest P_i at the instant of the call arrival. Additional rules may be needed if the values of P_i can be the same for two different routes. This strategy could be called: strategy of the mini-max loaded section. Such a dynamic strategy, which by no means intends to be an optimal strategy, would probably tend to balance the traffic handled by each section.

2.2.3 *Time Dependence*

If the application of the rule defining a routing strategy requires a clock (depends on real time) the strategy is nonstationary or transient. If not, the strategy is stationary. The strategies defined in the above examples were stationary; an example of nonstationary strategies will now be given. Consider again the network of Figure 1 and assume exchanges E and B are transit exchanges so that two routes are possible for a call from A to C. If this network is an international network it may happen that busy hours of sections EC and BC do not coincide [2] and do not overlap. Then, a simple nonstationary strategy is to route A-C calls via exchange B during the a priori busy hour of section EC and reciprocally via exchange E during the busy hour of section BC, both busy hours being determined from other traffic flows. Considerable savings in the number of circuits can be obtained in that way as compared with a calculation of the number of circuits that would not take into account this noncoincidence of busy hours.

In fact, the nonstationary strategy that has just been described could be replaced by a dynamic strategy, but the latter would need a continuous measurement of the occupancy state of sections EC and BC whereas the former implies the measurement (from time to time for updating) of the busy hours of these two sections, excluding traffic flow between exchanges A and C.

2.2.4 *Cost Dependence*

All the examples given above concern cost-independent strategies. In a cost-dependent strategy, the route chosen is that for which some cost function is minimal. The cost function may involve the topologic or metric length of the routes.

2.2.5 *Quality Dependence*

The route chosen for routing a call may also depend on the transmission quality (signal/noise ratio) of the different sections involved in the possible routes. This may be the case in networks using heterogeneous transmission techniques (metallic wires and radio links for instance).

2.2.6 *Mode of Route Selection*

In a step-by-step routing strategy, the originating exchange chooses a free outgoing group of circuits according to some prescribed rule (which can itself be classified in the same way as were strategies in the preceding sections) and establishes a connection over this section. The next exchange thus reached operates again in the same way, and so on, until the desired exchange is reached.

In a right-through routing strategy, the route is selected according to the well-known principle of conditional selection, that is, no part of the route is established before the identity of the route is completely determined, which implies having some knowledge of the complete network somewhere.

An intermediate mode of selection is obtained in step-by-step strategies with possibilities of crankback [4]; if in an intermediate exchange all the outgoing circuits which could be used to reach the next exchange are busy, the intermediate exchange can ask the preceding exchange to try another route.

3. Optimization Criteria

The research of an optimal strategy implies first of all that an optimization criterion has been defined, otherwise the word optimal would not have any meaning.

Criteria have been proposed by Rapp [6] for network optimization, assuming a given routing strategy (alternate routing). The value to be minimized is either the cost of the circuits under blocking constraints or the total cost of the circuits and of the blocked traffic, the cost of the latter being expressed as the cost of the subscriber's time.

As regards optimization in telecommunication networks three problems can be considered.

(A) The most general problem consists in calculating the number and location of exchanges, the number of circuits between each pair of exchanges, and in determining the best possible routing strategy for a given traffic pattern with blocking constraints expressed as the specified maximal loss probability for each traffic flow. The function to be minimized is the overall cost of the network under the blocking constraints and the results are the network configuration and the optimal routing strategy. This general optimization problem has hardly been approached up to now.

(B) A restricted optimization problem is the same as the preceding one, but without trying to find an optimal routing strategy; one fixed routing strategy is assumed. The result is the network configuration. This problem has been studied by Rapp [6], using alternate routing as a strategy.

(C) The other complementary restricted problem is to determine the routing strategy that minimizes some function under some constraints when the network configuration (number and location of exchanges, number of circuits) is given. The result is an optimal routing strategy. This problem has been studied by several authors, namely by Weber [4] who gave qualitative rules, but no optimal strategy was found even in simple cases.

Only this third problem, which in fact consists in determining the best use of an existing network, will be considered in the following. We shall first discuss the optimization criteria.

3.1 Traffic Handling Capacity

The most important requirement for an optimal strategy is obviously to be such that the (given) network handles the largest possible amount of traffic or, better, the largest possible number of erlang-kilometers, since the importance of a call increases with the distance covered. Alternatively, as far as the charging method does reflect the importance of the service given, the quantity to maximize could be the ratio return/assets. But this is by no means sufficient; telephony is not only a commercial institution that must make a profit but also a social institution that must give as equitable and as good a service as possible to every user (in our case to every traffic flow).

3.2 Grade of Service

As just mentioned the grade of service should be about the same for every traffic flow. It is easy to see, on simple examples, that in some cases, maximization of the traffic handled would lead to complete blocking for some traffic flows. Obviously, this cannot be accepted. There are several ways of specifying the grade of service.

(A) The loss probability is given for each traffic flow; generally, it is not possible to satisfy a prescribed grade of service, even approximately (see Ségal [7]) for each traffic flow and it is doubtful that an optimal strategy can be found under such strict conditions.

(B) The loss probability of each traffic flow must be smaller than some prescribed value, which may not be the same for every traffic flow; such conditions are much easier to realize than the above ones.

(C) The loss probability of each traffic flow must be in a prescribed interval; this might lead to incompatibilities if the interval is too small.

(D) The loss probability of each traffic flow must be smaller than some prescribed value and the variance of the different loss probabilities must be as small as possible; this would satisfy the above-mentioned equity criterion.

Whichever of these specifications may be required, they will appear as constraints in the optimization process where the function to be maximized is the total traffic handled.

3.3 Sensitivity to Overload

In the example given in the next section it will be seen that a routing strategy that is better than another one for a given value of offered traffic may be worse for another value of offered traffic. This effect is very important in practice because networks are calculated for a nominal value of the traffic matrix but overloads are frequent. Therefore, it seems that a comparison criterion should include some clause concerning sensitivity to overload. For instance, one strategy is better than another if the former corresponds to a smaller loss probability within a certain range of traffic offered (including the nominal value and a 10 or 20 percent overload). Alternatively, the maximal loss probability could be specified not only for the nominal value of the traffic offered but also for a certain percentage of overload. These are additional constraints on the optimization process.

3.4 Cost Considerations

Finally, the optimization criterion might be expressed in terms of cost; instead of the traffic lost, the function to be minimized would be a cost function involving the cost of a lost call (variable for each traffic flow) and a cost ratio depending on the length of the route to be used. Constraints such as those indicated in Sections 3.2 and 3.3 should also be included either in terms of blocking or in terms of cost.

4. Simulation Results

An optimal routing strategy cannot be determined of course by simulation but only by a theoretical approach. But since theoretical methods appear to be inefficient to solve the problem, simulation techniques can be expected to lead to a relative optimum in certain particular classes of routing strategies. Such was the aim of the work presented in this section.

The network considered is shown in Figure 2. This simple symmetrical network is composed of 4 exchanges completely interconnected by 6 sections; each section is composed of 2 one-way groups of circuits.

The network is moreover completely symmetrical from the points of view of topology, traffic, and routing strategies. Such a simple network has been chosen in order to eliminate as many parameters as possible, making it easier to compare several strategies for different grades of service.

The following notations are introduced.

n will denote the number of circuits per one-way group ($2n$ circuits per section).

A will denote the traffic offered in erlangs from one exchange to any other exchange; for instance, traffic between exchange A and exchange B is equal to A erlangs in each direction and this is true for any pair of exchanges: the total traffic of the network is $12A$ erlangs.

B will denote blocking, that is, the loss probability for each traffic flow (which is the same for any pair of exchanges since the network is symmetrical as are the strategies considered).

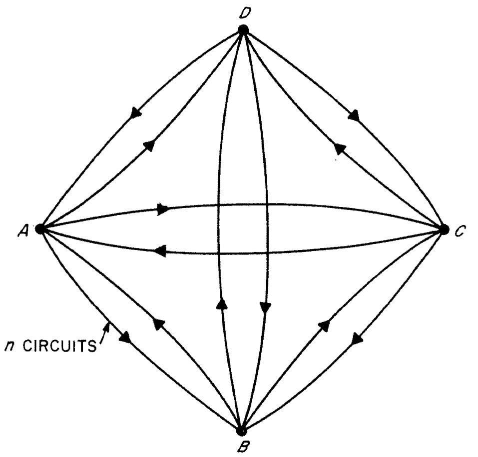

Figure 2—Simple 4-exchange network.

The 5 different routing strategies that have been compared are all stationary, deterministic, and cost independent; conditional selection is assumed (see Section 2.2).

The following assumptions have been made for the simulations.

A1—Traffic offered A is Poisson (purely random).

A2—Holding time has a negative exponential distribution function.

A3—Internal blocking is neglected even for transit calls. It is well known that subscribers do not have full access to the outgoing circuits of their exchange: internal blocking may occur and the variance of the traffic offered is smaller than that of a Poisson traffic. Both effects are neglected as well as the internal blocking in a tandem exchange.

In a first step of the simulation study, 4 strategies were considered.

S1, Direct strategy. This simplest strategy is taken as a reference; each call can use only the direct route (of length 1). No simulation is needed since with our assumptions the blocking B is given by the Erlang loss formula.

S2, 3-route sequential strategy (Section 2.2.1). There are 3 possible routes for each call, 1 of length 1 and 2 of length 2. For a call from exchange A to exchange B, routes are hunted in the following order: *AB, ACB, ADB.* Routes for other traffic flows are easily obtained by circular permutation.

S3, 5-route sequential strategy. This is the same as the previous strategy but with 2 additional possible routes of length 3. For a call from exchange A to exchange B, the possible routes are, in this order: *AB, ACB, ADB, ACDB,* and *ADCB.* For other traffic flows, circular permutation gives the ordered list of the possible routes.

S4, Dynamic strategy (Section 2.2.2). This strategy will be explained for an *AB* call, since it is also completely symmetrical.

The first route chosen is route AB if it is not blocked, that is, if there is at least 1 free circuit in the oriented group AB. If not, routes ACB and ADB are considered. If 1 of them and only 1 is not blocked, this route is chosen. If both are not blocked the choice is made as follows.

Let n_1, n_2, n_3, n_4 denote the number of busy circuits in the oriented groups AC, CB, AD, DB, respectively, at the instant of the choice. (n_1, n_2, n_3, and n_4 are all smaller than n.) Let n' denote the larger of numbers n_1, n_2 and let n'' denote the larger of numbers n_3, n_4. Then route ACB is chosen if $n' < n''$ and route ADB is chosen if $n'' < n'$. If $n' = n''$, choice is made at random.

If routes AB, ACB, and ADB are blocked, choice is made, if possible, between routes $ACDB$ and $ADCB$ in the same way as above.

Figure 3 gives the results of blocking B versus traffic offered A for $n = 50$ circuits per 1-way group. A large range of traffic was considered since one of the main aims of the study was to compare the sensitivity to overload. Curve 1 for direct strategy *S1* is simply the Erlang curve $B = E_n\ (A)$. Curve 2 gives the value of B for the sequential strategy *S2*; it was found that for the other sequential strategy *S3* the value of B was not significantly different from that of strategy *S2*. This is nearly true also for dynamic strategy *S4* except for very small or very high traffic offered but the difference remains very small (see curve 3).

Figure 4 gives similar results for $n = 10$ circuits.

The most striking point is that, in both figures, curve 2 (or 3) cuts curve 1 at a 3-percent blocking for 50 circuits and at a 10-percent blocking for 10 circuits. Below these values nondirect strategies are better than the direct strategy but above these values the direct strategy is better. In other words nondirect strategies are more sensitive to overload than is direct strategy. This effect is all the more pronounced as the number of circuits per group is increased. A provisional conclusion is that nondirect strategies that lead to use of a longer route than the direct strategy are more interesting in small-capacity networks than in networks having large groups of circuits.

Another conclusion is that overload conditions should be introduced in the specifications of a telecommunication network because of the differences in sensitivity to overload that characterize the strategy used. Consider for instance Figure 3. If the network is designed with 1-percent blocking (38 erlangs) with direct strategy *S1*, the blocking for a 10-percent overload will be about 3 percent and for a 20-percent overload the blocking is 6 percent. For the same values of traffic with other strategies, the figures are 0.1 percent for the nominal value, 3 percent for

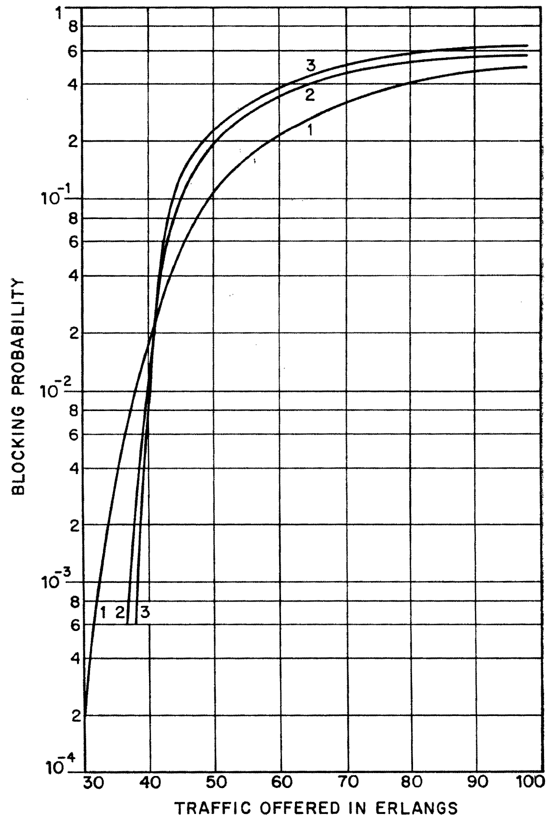

Figure 3—Simulation results for $n = 50$ circuits. Curve 1 is for strategy *S1*, curve 2 for *S2* and *S3*, and curve 3 is for strategy *S4*.

a 10-percent overload, but 12 percent for a 20-percent overload (which is not exceptional). Furthermore, if the network is initially dimensioned at a 1-percent blocking with strategy *S2,* for instance, the nominal traffic value is higher (40 erlangs) but for a 10-percent overload the blocking is 7 percent and for a 20-percent overload the blocking is 16 percent.

Looking at Figures 3 and 4, it appears that a "good" strategy should be such that it behaves roughly like the direct strategy for high traffic values and like strategy *S2, S3,* or *S4* for small traffic values. An attempt in this direction was made with the following strategy.

S5, Improved dynamic strategy. There are 3 possible routes for each call. For instance, routes *AB, ACB,* and *ADB* are for an *AB* call. Direct route *AB* is first chosen if not blocked. If route *AB* is blocked, then routes *ACB* and *ADB* can be used if and only if the number of busy circuits of each oriented group to be used is smaller than x (with $x < n$). Then the choice between both routes is made in the same way as in strategy *S4.* The essential feature of this strategy is that $n - x$ circuits are reserved in each section for direct traffic.

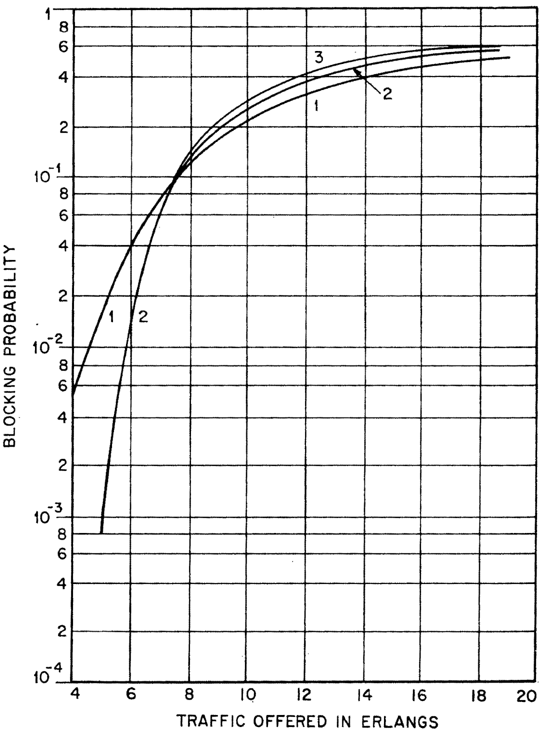

Figure 4—Simulation results for $n = 10$ circuits. Curve 1 is for strategy *S1,* curve 2 for *S2* and *S3,* and curve 3 is for strategy *S4.*

For $x = 0$, strategy *S5* is the direct strategy *S1,* and for $x = n$, strategy *S5* is between strategy *S2* and strategy *S4.* Therefore x must be small enough so that *S5* behaves like *S1* for high traffic and x must be large enough so that *S5* behaves like *S2* or *S4* for small traffic.

The problem was therefore to determine the best value of x, which was done in the following way. We have considered the traffic value (42 erlangs) corresponding to the crossing point of curves 1 and 2 in Figure 3, as a point where the difference should be the more significant, and for this traffic value we have obtained the curve shown in Figure 5, which gives the value of the blocking B versus x. For 42 erlangs the best value of x is thus 47 (approximately since the confidence interval was a bit larger than the difference between the values of B for $x = 46$ and $x = 47$). Then, using strategy *S5* with $x = 47$, the network was simulated for several values of traffic offered A. The results are shown in Figure 6 where curves 1 and 2 are the same as in Figure 3 and curve 3 corresponds to strategy *S5* with $x = 47$.

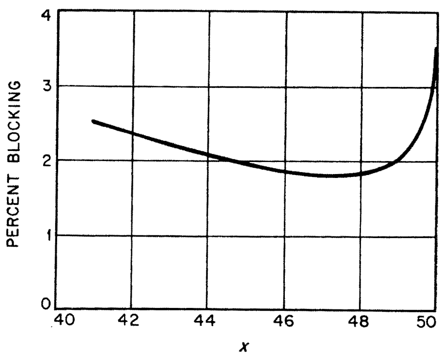

Figure 5—Influence of parameter x on blocking probability B for strategy *S5.*

It can be seen from Figure 6 that this new strategy is much less sensitive to overload than *S2, S3,* or *S4;* if the network is designed for a loss probability of 1 percent, then strategy *S5* (with $x = 47$) is always better than direct strategy *S1,* up to an overload of about 20 percent. Moreover, except for very small values of *B,* strategy *S5* is always better than strategies *S2, S3,* and *S4.*

Results such as shown in Figures 5 and 6 were not found for 10-circuit groups. But this is precisely a case where no improvement is necessary. Strategy *S5* needs, on the other hand, a more precise knowledge of the state of the network than the other strategies; for every section (or oriented group) the routing control units must know whether the number of busy

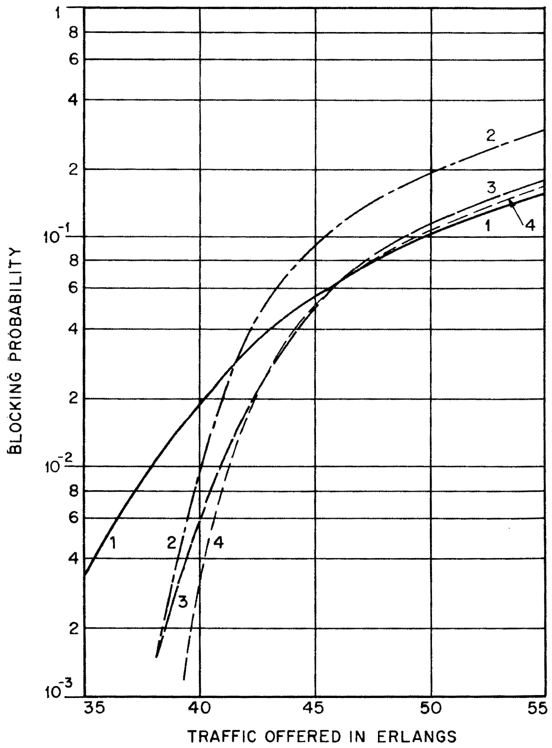

Figure 6—Improvement due to strategy *S5* for $n = 50$ circuits. Curve 1 is for strategy *S1* and is exact. Curve 2 is for strategy *S2* by simulation. Curve 3 is for strategy *S5* for $x = 47$ by simulation. Curve 4 is for strategy *S5* for $x = 47$ and is calculated approximately.

circuits is smaller or larger than x, which represents important data traffic. But the curve of Figure 5 shows the optimum is very flat; an approximate knowledge should be sufficient. In [8], a method is proposed using overlapping classes of occupancy which results in a considerable decrease in the data traffic. For instance, it is shown that, if it is sufficient to know that the number of busy circuits is smaller than $x + p$ or larger than x, then the data traffic is divided by $p - 1$.

5. Approximate Calculations

It is often useful to be able to obtain rapidly and cheaply a rough idea of the blocking in a network when a specific routing strategy is applied. It is generally possible to apply in any network with any routing strategy the method described below by two simplifying assumptions.

Assumption 1: All the different traffic flows offered to a specific section (or oriented group of circuits) are assumed to be Poissonian so that the Erlang formula applies. In fact overflow traffic is not Poissonian, but in general a large part of the total traffic offered to a section is Poissonian.

Assumption 2: The traffic handled by a section is independent of the traffic handled by another section, and the overall blocking can be calculated according to Lee's method [9].

Again this second assumption is approximate since some calls may use several sections (routes of length larger than 1) but the number of calls using 2 given sections at the same time is generally small compared with the total number of calls handled at this time by each section.

Generally, the effects of assumptions 1 and 2 are opposite and it will be seen that they often compensate.

Two examples will now be given, one for strategy *S2,* the other for strategy *S5* in the network of Figure 2.

With strategy *S2* the traffic offered to each group of one-way circuits can be expressed as the sum of three terms.

(**A**) Direct traffic (first choice) A.

(**B**) Second-choice traffic: 2 traffic flows can use a given section as second choice; their intensity is Ap if p denotes the probability that the n circuits of an oriented group are fully occupied; they are offered only if the other group in tandem is free, that is, with probability $(1 - p)$; the total second-choice traffic offered to a particular group is therefore

$$2 \cdot Ap \cdot (1 - p).$$

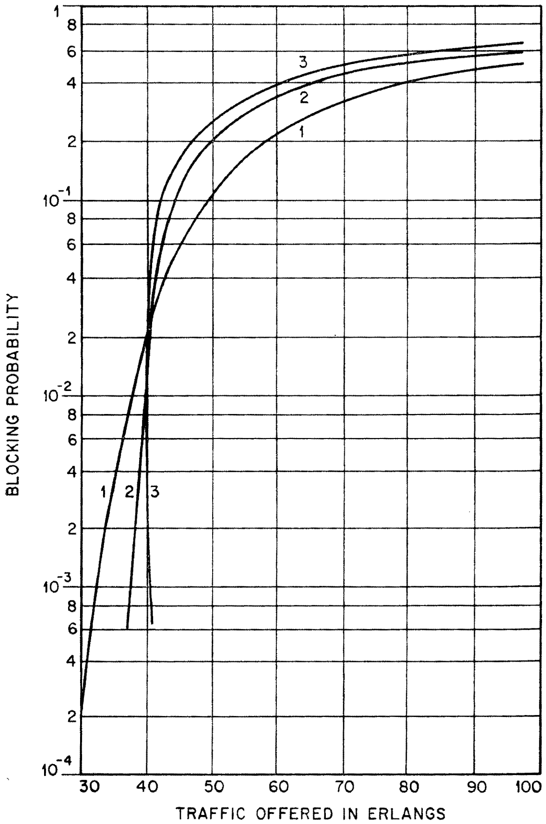

Figure 7—Comparison between simulation and approximate calculations for $n = 50$ circuits. Curve 1 is for strategy *S1*. Curve 2 is for strategy *S2*. Curve 3 is for approximate calculations.

(**C**) Third-choice traffic: 2 traffic flows can use a given group, their intensity is

$$Ap(2p - p^2),$$

and the total third-choice traffic offered to a particular group is

$$2Ap(2p - p^2)(1 - p).$$

According to our first assumption, p is then given by the Erlang formula

$$p = E_n(A') \qquad (1)$$

$$A' = A[1 + 2p(1 - p)(1 + 2p - p^2)] \qquad (2)$$

and must be calculated by iteration. According to the second assumption the overall blocking B is given by

$$B = p(2p - p^2)^2 = p^3(2 - p)^2. \qquad (3)$$

The results are given for strategy *S2* by curve 3 in Figure 7 (n = 50 circuits) and Figure 8 (n = 10 circuits).

In the same way as above, blocking B with strategy *S5* can be calculated.

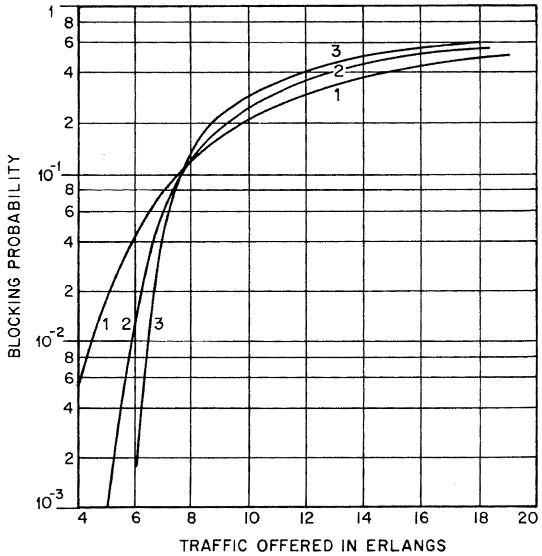

Figure 8—Comparison between simulation and approximate calculations for $n = 10$ circuits. Curve 1 is for strategy *S1*. Curve 2 is for strategy *S2*. Curve 3 is for approximate calculations.

Let p denote as above the probability that a group of n circuits is blocked and p' denote the probability that the number of busy circuits in a group is larger than or equal to x. Probability p' is given by

$$p' = p\left[1 + \frac{n}{A'} + \frac{n(n-1)}{A'^2} + \cdots + \frac{n(n-1)\cdots(x+1)}{A'^{n-x}}\right] \quad (4)$$

where p and A' are found to be

$$p = E_n(A') \quad (5)$$

$$A' = A[1 + 2p(1-p')^2(1+2p'-p'^2)]. \quad (6)$$

The above three equations can be solved by iteration. The overall blocking is given by

$$B = pp'^2(2-p')^2. \quad (7)$$

Numerical results are shown by curve 4 of Figure 6 for strategy *S5* with $x = 47$.

Although the results shown may seem satisfactory to get a rough idea of the blocking with a specific strategy, this approximate method may in certain cases (mainly for small blocking) give erroneous results and consequently this method should not be used without caution, that is, without simulation support.

6. Conclusion

A first general conclusion is that simulation techniques can be of a great help for theoretical investigations on traffic in telecommunication networks.

As regard the comparison made between several routing strategies, two points are worth noting.

1. Sequential routing strategies, as compared with the direct strategy, are mainly interesting for small-capacity networks, that is, involving small groups of circuits. The gain in traffic at a 1-percent blocking level is 35 percent for a 10-circuit group instead of 6 percent for a 50-circuit group.

2. Sequential routing strategies are very sensitive to overload mainly in large-capacity networks. Routing methods with circuit reservation for direct traffic are better in that case.

Finally, it should be added that the present study is only an attempt toward routing optimization. The discussion of Section 3 shows that even the question of defining a routing optimization criteria for an existing network is still open.

7. Acknowledgements

The author expresses his gratitude to Mrs. Bernard, Mr. Senaize, and Mrs. Tessier for their assistance in the preparation and operation of the simulation programs that were essential to this study.

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Magnetische Werkstoffe und ihre technische Anwendung (Magnetic Materials and their Application in Engineering)

By Dr. Carl Heck of Standard Elektrik Lorenz, this text establishes a bridge between the thinking of the producer and the user of magnetic materials. It is particularly helpful in view of the rapid progress in the field of magnetic materials.

The introductory sections cover magnetic phenomena and properties, with emphasis on ferromagnetic and ferrimagnetic materials. Following are sections on materials for permanent magnets. Metal and oxide materials for soft magnets and their fields of application are presented together.

The selection of the most appropriate material for a given application is greatly aided by a tabulation of available materials and suppliers of them in various countries.

The book comprises 711 pages, 547 illustrations, and 156 tables, and includes a voluminous index and list of references. Its format is 18 by 24 centimeters (7.1 by 9.5 inches) and it can be obtained from Dr. Alfred Hüthig Verlag, Heidelberg, Germany, for DM 108.

Potentialities of an Integrated Digital Network

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1. Introduction

Communication networks have developed with immense rapidity in the past decades on a foundation of analogue transmission over physical circuits and frequency-division-multiplex carrier organized to transmit the 300–3400-hertz bandwidth normally considered adequate for voice communication. Limited communication at wider bandwidths has been provided, but the only switched service available on any scale other than voice has been low-speed (50-and-75-baud) telegraphy.

Pressures of increasing traffic demands and requirements for greater versatility and variety of modes, combined with the emergence of new technologies, call for the examination of the possibilities of a new and potentially more versatile network based on digital transmission.

The exploitation of this potential versatility is a perfectly feasible proposition. It will, however, inevitably involve very many planning problems and call for the abandonment of some traditional attitudes.

There is already becoming available a considerable amount of literature on the technical aspects of pulse-code-modulation transmission and switching, but not, as yet, very much on the broader system issues. This article is written in the hope that it will convey something of the great potential scope of such a network, and indicate that, despite the apparently revolutionary nature of the concept, a perfectly acceptable transition is possible. It is felt that discussion of these broader issues is becoming a matter of urgency, so that the initial implementation can be organized against a background of a reasonably agreed and defined set of goals.

2. Technical Background

Although this article is primarily concerned with the network implications, it seems necessary to develop first a picture of the technological situation that will indicate the fundamental advantages and the extent to which existing developments are already making the necessary tools available.

2.1 Definition and Properties of Digital Transmission

By digital transmission is meant a transmission capability designed to convey digital information—normally in binary form—and incapable of direct conveyance of any other type of information. Any analogue information to be conveyed over it must first be converted to a digital form.

This class of transmission presents two new features as compared with traditional methods. Firstly, multiplexing is on a time-division basis as opposed to the frequency division of traditional systems. Secondly, the linear amplifiers are replaced by digital regenerators.

If theoretical perfection were attainable, this use of regenerators would mean no deterioration of transmission, whatever the length of circuit. In practice, economically feasible regenerators are inevitably compromises, with slight imperfections in the execution of the process, but nevertheless their performance is adequate to a very high standard of freedom from accumulated error, even on long circuits.

This property makes it feasible and economic to exchange signal-to-noise ratio for bandwidth to the extent of using bandwidths an order of magnitude greater than are practicable in the analogue mode, at any rate in enclosed media such as paired cable or coaxial cable.

2.2 Pulse-Code-Modulation Speech

The conversion of speech to a digital form by quantization and coding, now known as pulse code modulation, was conceived many years ago, and it is only relatively recently that the availability of suitable solid-state devices has made it feasible to build practical systems which are economically viable. It has now been shown by actual field experience that such systems provide the cheapest way of obtaining circuits on paired cable over distances of 10 to 20 or 30 miles (16 to 32 or 48 kilometres) with every indication that the distances over which it will be economically attractive will rapidly increase.

In the United States of America, the application of pulse-code-modulation systems to transmission over existing junction cables has proved to be quite startlingly successful, and its rate of introduction has exceeded that of any previous carrier system.

2.3 Pulse-Code-Modulation Switching

2.3.1 *Cost and Performance*

Although the application of pulse-code-modulation junction carrier systems has been demonstrated to be valid over a wide range of applications on an audio-to-audio basis with conventional switching, this method of use prevents the exploitation of certain basic characteristics of pulse code modulation. For example, on a pulse-code-modulation junction circuit of a few miles in length, the main degradation in the quality of transmission, together with a high percentage of the total cost, occurs in the terminal equipment.

If, therefore, switching could be effected on a digital basis, even at the same cost as for conventional switching, tandem connections would be spared both the cost of two pulse-code-modulation terminal units and also the additional transmission degradation resulting therefrom.

In recent years, therefore, considerable effort has been devoted to the problems of switching speech circuits while the information is still in the digital form. This would begin to realize the capabilities of the mode to limit the build-up of noise and distortion and to secure much more uniform performance.

Apart, however, from this enhancement in performance, it is becoming increasingly evident from the work of Laboratoire Central de Télécommunications that the combination of time-division switching with time-division multiplexing, and the compatibility of the various elements in the system, opens the way to immense reductions in the cost of transit switching.

Time-division switching has been for years considered as potentially the most economic answer to the switching problem, but has suffered from acute difficulties on crosstalk and transmission stability and has involved expensive interfacing with analogue transmission. When applied to digital information, transmission problems such as crosstalk are greatly reduced, and the way is opened to intermediate storage and regeneration which give great flexibility in cross-office organization. When to these are added the extremely simple compatibility with the new transmission mode, the resultant impact on overall cost is very great indeed.

2.3.2 *Synchronization*

The British Post Office has presented accounts of an approach they are studying to a completely synchronized network. Solutions are, however, possible on a quasi-synchronous basis, one of which was described in reference [3]. With the type of clock accuracy now obtainable, the performance degradation of such a system can be made insignificant, and it is believed that the cost will not be greatly significant. The flexibility and robustness of this approach may be well worth the slight cost penalty.

2.3.3 *Adaptation to Local or Other Audio Channel Traffic*

Although the pulse-code-modulation switch has so far been described as operating between pulse-code-modulation transmission systems, it can also handle audio channels by interface units called local adapters. These are coder-decoder units which are simpler in type than the terminals of a regular junction system, because all the clock and distributor functions are looked after by the switch. The interface with the switch is thus fully synchronous and hence simpler than the regular line interface. There is growing confidence that the cost of this arrangement will be sufficiently low for pulse-code-modulation switching to be still highly attractive, with a largely—even predominantly—audio transmission environment.

2.4 Signalling

The type of system now widely favoured employs 56 kilobits per second for voice transmission, so that the provision of a relatively limited addition to the total system bit rate makes available any or all of the following:—

(A) High-speed end-to-end signalling outband, but directly associated with the speech channel.

(B) Link-by-link signalling also directly associated.

(C) Order-wire or common-channel signalling as required.

(D) High-speed inter-register signalling.

The channel-associated signalling capability is totally outband, that is, completely free from voice interference and similar problems, and is very cheaply received and interpreted.

Outstanding problems are therefore related not to the potential signalling capacity, but to the optimum organization of its use in a wide variety of circumstances.

2.5 Extension to Long-Haul Systems

The application of pulse code modulation, to date, has been confined in the main to 24-channel systems in deloaded paired cables with regenerators at loading-coil spacing. In this mode, the line cost is acceptable as compared with terminal costs up to 20 or 30 miles (32 or 48 kilometres). For longer routes, this class of system is too limited in bandwidth to compete successfully with wider-band frequency-division-multiplex approaches. Considerable work has already been carried out on the study of systems in such classes as 96 channels on balanced paired cable, 384 channels on small coaxial cable, and an experimental 224-megabit-per-second system on 9-millimetre coaxial cable described by Bell Telephone Laboratories in the United States. This latter would provide some 3500 channels.

2.6 Impact on Data Handling

The obvious attractions of a network of this type for the handling of data are the direct consequence of the high bit rate employed for the transmission of speech and the ready accessibility of the bit capacity of any channel for the alternative transmission of other digital information. The speech channel of the class of pulse-code-modulation system most widely studied provides immediate availability of a 56-kilobit-per-second digital stream. The full use of this speed would involve a synchronous interface with the peripheral equipment. Where pulse-code-modulation working is extended to the local exchange so that the "tail" length is only that of a regular subscriber line, this presents no fundamental problem for most likely modes of use and would be an extremely cheap method. Where, however, this procedure cannot be employed, relatively cheap asynchronous interfaces are feasible up to speeds of just under 48 kilobits per second.

3. Economic and Performance Advantages of a Digital Network

With this outline of the technologies available as a basis, let us now examine the economic and performance attractions of a hypothetical completely digital national network. We will then proceed to an examination of the transition problems involved in the evolutionary attainment of such a goal.

3.1 Transmission Uniformity

The key performance gain in the handling of voice is that, apart from the impairment due to the analogue-digital conversion at the ends of a complete connection, there need be no significant degradation throughout the network. In particular, the overall transmission loss from end to end, and the loss–frequency characteristic, will be for practical purposes completely independent of the route traversed or the number of digital switching points involved.

In the handling of data and other naturally digital information, related improvements in performance are attainable. Certain precautions, appropriate to the type of information, may be needed to counter mutilation due to slip consequent on imperfect synchronization of clocks, but otherwise the information is handled with a complete absence of the cumulative analogue distortions inevitable in the traditional network.

3.2 Speed and Versatility of Switching and Signalling

Time-division switching is inherently faster than any other type of switching available to us, and the liberal signalling capacity enables signalling speeds to be comparably fast, with a net result that the entire process of establishing a call through a switch including routing signals can, if necessary, be held to a figure of the order of 100 milliseconds or less.

3.3 Low Cost of Switching and Terminals

Although the actual line cost, that is, the cost per channel-mile without terminals, is unlikely to be less than that of wide-band frequency-division multiplex—indeed as will be explained later in the transition phase it may be somewhat greater—there is increasing confidence in the prospect of considerably lower switching and terminal costs. There is every hope that, in a comparison with present frequency-division-multiplex carrier and audio switching, the cost reductions will be truly startling.

Figure 1 shows, at representative present price levels, the cost of switching a long-haul connection at one intermediate point. Line *A* shows the basic line cost, line *B* adds the share cost of a representative crossbar switch, line *C* adds voice-frequency signalling and relay sets, and line *D* adds frequency-division-multiplex channel ends. The heavy line *a* indicates a line cost for pulse code modulation assumed to be 50-per-cent greater than that of frequency-division multiplex, and line *b* adds switching (a conservative estimate for 1970) including channel ends and signalling. This represents a reduction in the cost of the centre of 4 to 1 which may well be exceeded. If frequency-division multiplex is being compared with pulse code modulation, the reduction in cost of signalling and channel ends means that a distance of some hundreds of miles would be needed before the adverse line cost assumed for pulse code modulation would upset the balance. It is to be expected that, by the time significant application

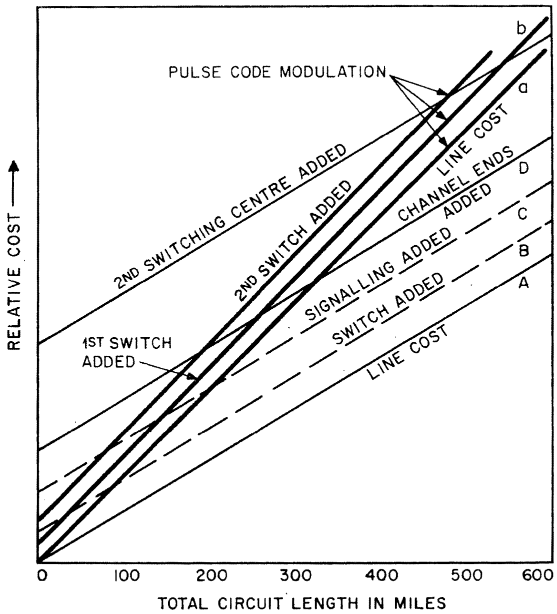

Figure 1—Comparison of pulse code modulation and frequency-division modulation for a toll connection with one or two intermediate switches. In the case of pulse-code-modulation switching, the equivalent of channel ends and signalling are included in the switch. These plots do not take into account the terminal channel ends and signalling, since to do so accurately involves more precise definition of the terminal exchange organization. In general the inclusion of these would improve the relative position of pulse code modulation.

to this length of circuit is seriously considered, the unfavourable balance in line cost, which is mainly a reflection of an assumption of somewhat lower-capacity systems, will have been eliminated.

The main point which is being emphasized here is, however, that in the connection of 50 to 100 miles (80 to 160 kilometres), which is very dominant in representative traffic in our areas, the cost of an interpolated switch in the present network is extremely damaging; in the pulse-code-modulation case it is a sufficiently small proportion of the total to be offset by a relatively modest gain in channel usage efficiency due to pooling of traffic. This, in conjunction with the performance advantage referred to above, presents opportunities for much more rational network planning, using switching as freely as needed to secure traffic efficiency and flexibility, while escaping the oppressive drive to avoid switching, even at the cost of very inefficient direct routes.

The preceding paragraph discusses a comparison with the frequency-division-modulation carrier situation. Figure 2 shows a corresponding set of curves for a comparison with 20-pound (0·9-millimetre) junction cable. Here, of course, pulse code modulation shows a lower per-mile line cost but a higher terminal cost. However, even the modest saving assumed in the switching cost results in pulse-code-modulation integrated working being worthwhile for tandem connections whose total length is 2 or 3 miles (3·2 or 4·8 kilometres). There is every hope that the price ultimately attainable for a pulse-code-modulation switch will reduce this distance effectively to zero.

Here again, economic and performance factors will make an increase in tandem working, including the liberal use of 2 tandem systems in succession, an attractive possibility.

Although, on physical circuits, pulse code modulation cannot claim savings in the signalling costs of regular automatic-to-automatic calls, wherever greater sophistication is needed, for instance in the handling of multi-metering over junctions in outgoing automatic toll calls, the possibility of very significant savings is re-introduced.

3.4 Economics of Data Handling

The great gain in data handling is a direct reflection of much-cheaper bandwidth in a very cheaply accessible form. Space does not permit of a detailed examination of the various ways of tackling the terminal area association. It is hoped to do this in a later article. It is sufficient for the moment to note that in the digital network we are considering:—

(A) Data speeds of up to 56 kilobits per second at a terminal expense less than that for present 1200-bit-per-second data modems, transmitted on what is really a voice connection costing no more, and in general significantly less, than a voice connection in the present network.

(B) A 2000-bit-per-second sub-multiplex network which has line costs less than for 50-baud voice-frequency telegraphy and terminal costs

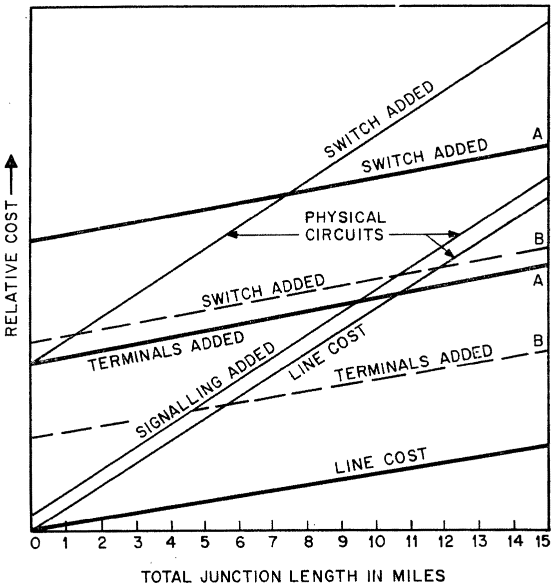

Figure 2—Cost comparison for local tandem connections of physical circuits and of pulse code modulation in which *A* costs are based on a conservative 1966 estimate and *B* on a still very conservative 1970 estimate.

very greatly less. (In some systems such as the present British Post Office standard, the line cost up to 24 channels per system is virtually non-existent, as it uses otherwise wasted spare capacity in synchronizing and signalling channels).

Detailed studies are not yet available, but there is every reason to hope that time-division-multiplex switching of this 2000-bit-per-second capability could result in very striking savings indeed as compared with present telex switching practices.

The potential users of these new capabilities are many, and true data might well be a minority source of traffic. The major uses may well be for text, and for black-and-white facsimile and its derivatives—displays, plotters, and the like.

3.5 Uniformity of Tandem and Toll Switching Designs

An additional very useful tool for the network planner is that, as a consequence of its natural employment of 4-wire switching, its high speed, and its fast versatile signalling, pulse code modulation provides the prospect of a basic high-capacity full-availability switch, economic over a wide range of sizes and functions. (By a full-availability switch is meant a switch in which, subject to some calculable blocking, any inlet can reach any outlet.) This means that the present distinctions between local tandem, toll outgoing, toll incoming, and toll transit switches may largely disappear, and we shall have available a universal class of switch which, with suitable variants in its control programme, may be used for any of these functions, and in fact for several of them simultaneously.

3.6 Extension to Local Exchanges

So far, we have considered, in the main, the tandem and toll networks. If we turn to local exchanges, at any rate large local exchanges in big urban or metropolitan centres, it may be seen that pulse-code-modulation switching still has much to contribute. Local switching is evolving in many different patterns, but very many of these are based on the overall structure reasonably related to the Bell System line-link-frame/trunk-link-frame association. Unless and until the digitizing of voice is taken right back to the subscriber's set (which, while it may come some day, is not being considered here) the line link frame cannot use digital switching, but the conversion of some or all of the trunk-link-frame capacity to digital switching is likely to have great attractions. It would be a natural fit for pulse-code-modulation tandem and toll junctions and could introduce a better economic basis for extending pulse code modulation to direct junctions. It would, we believe, be in its own right at least as cheap and probably cheaper than alternative approaches, even when only a fraction of the total junction plant is converted to pulse-code-modulation operation; finally, it would open up prospects of simplification and cost reduction in the line-link-frame area.

A pulse-code-modulation trunk-link-frame capability of the type suggested does not differ basically from the tandem transit switch we have been discussing. The main differences would be that, on the local side, it would be served entirely by local adapters, and that for realization of the full potential of the partnership the central control should be organized to serve both trunk-link-frame and line-link-frame sections.

Pulse-amplitude-modulation switching has obvious attractions for the line-link-frame stage, apart from the perpetual difficulty of high cost of the subscriber's line terminal and its bandwidth limitation. The importance of the latter is mainly a function of the expectation of extended use of the communication network for non-speech modes—high-speed data, facsimile, et cetera. If it is desired to leave the way open for these wider capabilities, then a space line link frame is desirable. Even here, however, a pulse-code-modulation trunk link frame is a valuable partner. The reason for this is that it is possible, in this mode, to create very-high-capacity full-availability frames (several thousand erlangs) and because of this, even in very large offices, small line link frames may be used without loss of traffic efficiency.

4. Practical Implementation

Examination of the problems of progressive introduction of the digital mode into existing networks is difficult on a completely general plane, since all administrations have their own special problems both in relation to network layout and characteristics of their existing switching practices. However, it does seem reasonable to attempt an illustration of the possible evolution in terms of the sort of hierarchical structure shown in Figure 3. This, although there are many variants, is representative of the basis of many national networks.

In such a network, the first immediate application of pulse code modulation is likely to be the replacement of physical circuits in the links shown in Figure 4. This is already beginning to happen. In many parts of the network the introduction of pulse-code-modulation tandem switching can greatly increase the economic attraction of this process, and by virtue of its speed, signalling flexibility, and transmission performance could lead to a much more effective merging of local tandem and toll centre functions.

This process of supersession of physical circuits by pulse-code-modulation carrier could logically extend fairly rapidly to the next order up in the typical toll network where regular frequency-division-multiplex carrier is still not very extensively used, that is, between toll and district centres. When, however, we consider the next step of penetration into long-haul operations, we are faced with an immense investment in frequency-division-multiplex carrier which cannot economically be superseded at any drastic pace.

If, however, we are to realize the potential of the digital network for highly economic handling of data, it is imperative to create at least a minimal national coverage. The approach which seems most hopeful here would be to install digital switching and transmission as indicated in the dotted heavy lines in Figure 5. This could be done with a reasonably limited investment, and would secure the achievement of two objectives:—

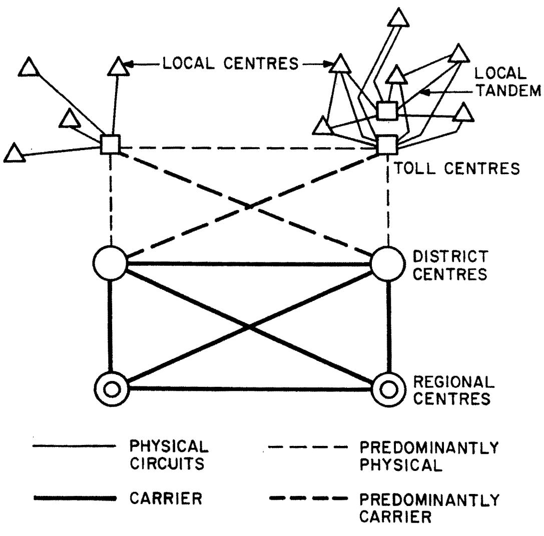

Figure 3—Typical hierarchical network.

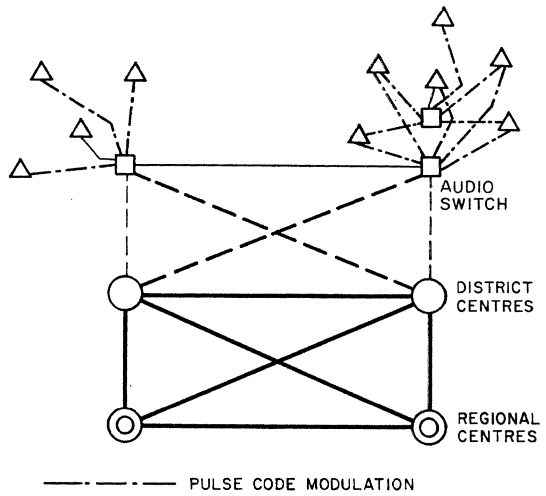

Figure 4—Typical hierarchical network showing first introductory phase in which pulse code modulation replaces physical circuits in the junction area.

(A) To provide a digital capability to serve as a basis for data handling over a national network, which, in conjunction with the junction area conversions already referred to, could be brought within reasonable access of all the more likely (urban) users and would admit of reasonably economic but slightly more expensive access by a limited number of more-dispersed users.

(B) To provide an extremely convenient network with transmission performance, speed, and signalling versatility to handle the "final route" voice traffic much more effectively than can be done with multi-switched frequency-division-multiplex connections. The traffic involved in this usage would be small enough to limit the rate of investment to something manageable but large enough in conjunction with the data usage to make the network viable.

4.1 Transmission Basis for Longer-Haul Usage

In selecting a transmission basis for this penetration into longer-haul sections, some initial compromise is probably necessary. A wider band capability than 24 channels on deloaded pair will be needed to hold line costs down to an inconspicuous level. On the other hand, for early exploitation, two factors limit the upward excursion. One is the need for further experience with very-high-speed digital logic, the other the need to control the investment pattern. The aim is to create a widespread network, albeit simple in its routing patterns. The initial cost of a comprehensive network based on, say, 3500-channel capacity (the equivalent of the Bell Telephone Laboratories' 224-megabit-per-second system) is likely to be excessive, and a more-reasonable solution may be found in a capacity of the order of 96 channels on unidirectional paired cable and about 384 channels on small coaxial cable, although further analysis of crosstalk limitations is needed before final capacities can be selected. The line cost per mile of these is likely to be somewhat higher than 960- or 2700-channel coaxial cable, which is why an admission of this possibility was included in Section 3.3. However, this slight adverse factor is much more than offset by lower terminal signalling and switching costs until very-long-haul links (greater than several hundred miles) are met.

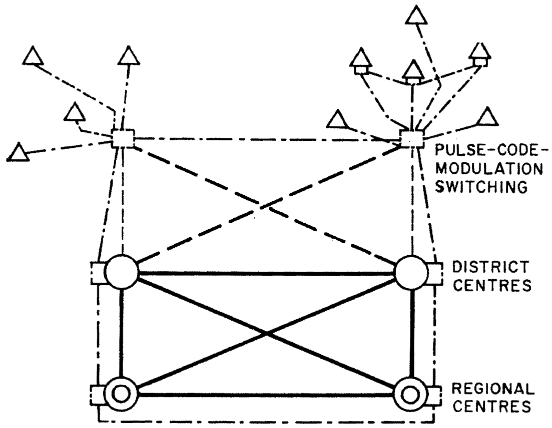

Figure 5—Typical hierarchical network showing beginnings of a national digital network which includes pulse-code-modulation switching for local tandem, toll, and pulse-code-modulation transmission and switching in long-haul backbone network.

In the case of unidirectional paired cable, many of the more highly developed countries already have a trunk network of such cables which was installed before the introduction of coaxial cables, and which is now used to provide from 24 to 60 telephone channels per pair. In most countries, these routes are already paralleled by high-capacity coaxial or microwave routes, so that the conversion problems would be minimal, and the opportunity would be provided to replace relatively old and bulky equipment in the existing repeater stations.

4.2 Terminal Area Evolution

In the authors' view, the inherent flexibility of the basic pulse-code-modulation switch and the associated line signalling provide ample freedom of manoeuvre in the organization of coordination with existing and future local-area switching practices. It has already been indicated that, after the initial step of using pulse-code-modulation junctions terminated on existing local exchanges, the next move could logically be the introduction of what we have called a pulse-code-modulation trunk link frame. This could cooperate with subscriber switching in existing modes such as step by step or in future modes such as crossbar reed relay or even pulse-amplitude-modulation time division.

It does, however, seem desirable to examine the resultant patterns in data handling.

Figure 6 shows a section of a network comprising a local exchange, a toll centre, and a toll transit centre. A possible sequence of events might entail the introduction of pulse-code-modulation junction carrier circuits as shown, and the introduction of pulse-code-modulation switching at the toll transit centre, providing access to the initial moderate-capacity digital transit network already alluded to.

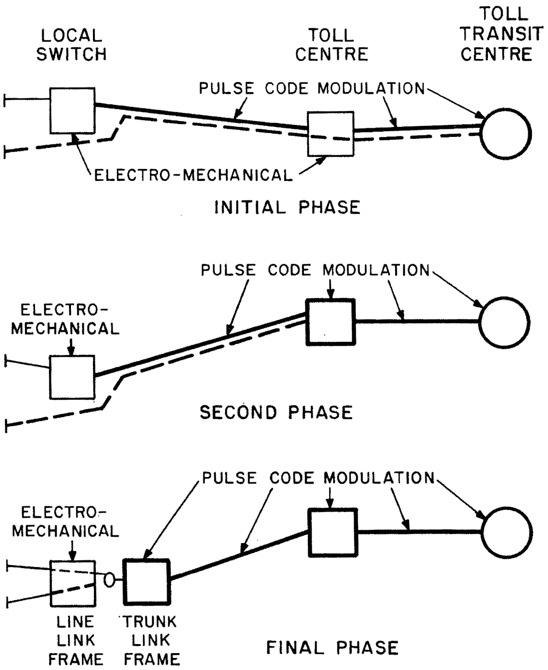

Figure 6—Accommodation of high-speed data with different degrees of pulse-code-modulation penetration.

If it is assumed that the existing local and toll switching is unsuitable for high-speed data, the initial phase would involve using predetermined pulse-code-modulation channels to the trunk transit centre as subscriber lines. This is not a highly economic arrangement, but could provide cheaper high-speed data service than any existing network. The 2000-bit-per-second sub-multiplex capability could again be used initially as a cheap method of providing long subscriber lines to a central switch.

When the toll exchange becomes pulse code modulated, it would be possible to arrange to carry out the switching of high-speed data subscriber lines back at the toll exchange, and thereby greatly reduce their length. Low-speed data may be switched as and where convenient.

With pulse-code-modulation penetration into local exchanges, a further step would be taken to provide cheaper high-speed data service. A possible final arrangement of a local exchange is shown. Here the line link frame or local switch section is assumed to be universal, that is, suitable for and used for switching a wide variety of traffic, which includes speech, high-speed data, and low-speed data, while at the interface with the pulse-code-modulation trunk link frame the various calls are sorted out into the mode of handling through the main network appropriate to their individual needs.

5. Conclusion

It has been possible in this short article to give only the briefest outline of the possible growth of a digital network. It is hoped that we have not only shown something of its attractiveness on grounds of economy and performance but have also succeeded in dispelling misgivings natural in regarding such a wide-ranging concept. We have also demonstrated that, provided the overall system approach is made in adequate depth and is not too restricted by over-traditional thinking, the new methods can be introduced in a manner compatible with existing practices, so that an ordered and economic transition is practicable.

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G. C. Hartley was born at Stoke-on-Trent, Staffordshire, England, in 1903. He graduated from Cambridge with a B.A. Honours degree in mathematics in 1924.

On graduation he joined Standard Telephones and Cables where, in 1930, he became head of its circuit design section. In 1943 he was placed in charge of switching development and by 1950 of advanced development. During 1959 he was seconded to ITT Communication Systems in the United States of America for special consultations on military projects until 1963 when he joined the Advanced Development Planning Group of Standard Telecommunication Laboratories.

Mr. Hartley has represented Standard Telephones and Cables on various outside technical committees. He is the author of several technical papers on switching and signalling and has been granted over 90 patents.

Jacques H. Déjean. Biography appears in *Electrical Communication,* volume 42, number 2, page 269; 1967.

Radio Relay Systems

Originally published in German under the title "Richtfunkverbindungen," this book is now available in English. The author is Dr. Helmut Carl of Standard Elektrik Lorenz.

This comprehensive presentation of radio link engineering includes numerous references to the pertinent literature and a list of technical terms and definitions.

The book is 15 by 22 centimeters (5.9 by 8.7 inches) and has 332 pages. It is available from Macdonald & Company, London, England, at 65 shillings per copy.

Dispersed Telecommunication Network Structure

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1. Introduction

The history of telephone switching systems shows a dominant tendency towards segregation in specialized devices of functions such as reception, logic or decision, sending, connection, et cetera.

The common use of these specialized devices can permit high efficiency, and the segregation of functions avoids compromises detrimental to the good execution of each function. For example the introduction of registers permitted routing towards the called office to be considered as a whole and made independent of the numbering plan.

The increase in efficiency obtained from commoning has significant economic effects that also permit useful improvements in the functions to be performed. Thus routing indicators permit alternate routing, which was economically out of reach with register-translators.

However, the more a device is specialized, the more its traffic is restricted, everything else being equal.

The high efficiency mentioned above is therefore obtained by a concentration of traffic on a small number of devices. Thus the consequences of faulty operation of one of them will be more serious as the number of pooled devices becomes smaller. In some extreme cases, two devices must be provided even though traffic would normally be handled by only one.

This concentration also stems from the use of faster techniques. The introduction of electronics into the control of telephone exchanges has progressively led to a search for maximum utilization of the speed of electronic devices to permit extreme concentration without any specialization.

The systems we have developed at the present time are deliberately directed toward centralized control by a more-or-less general-purpose information processing unit; it is evident that other organizations are working in the same direction [1].

In an organization of this kind specialized devices are to be found in the form of subroutines in the control unit memory; specialization is being transferred from hardware to software. Here again duplication of some equipment may become necessary to meet the reliability requirements.

In this liaison between telephone systems and information processing systems, it is obvious that the established economics of the latter will have to be applied to the former.

The information processing specialists have clearly demonstrated the economic advantages of concentration and consider the price of a machine to be roughly proportional to the square root of its speed. Thus, everything else being equal, the cost of doing a certain task will be approximately halved if done on a machine four times as fast.

It is clear that in the case with which we are concerned, a limitation is the fact that everything else is not equal. Three methods naturally come to mind if we are to concentrate an ever-increasing control traffic in one unit.

The first method consists in increasing the size of the exchange. Although it is relatively easy to design a telephone system with centralized control that is economical for large capacities, we run up against a price barrier when the capacity is reduced because the central unit assumes an increasingly larger part of the overall cost. Thus for a system in the course of development, the cost of the central unit is estimated as 43 percent of the total cost for a 2000-line exchange, while it is estimated as only 14 percent for 10 000 lines. The required number of switching units is very closely related to the number of subscriber lines.

No consideration will be given to an appreciable increase in subscriber line lengths to increase the size of the exchange.

The second method consists in avoiding this limitation of exchange capacity due to the price of the subscriber lines by using line concentrators or satellite switching units. These would be controlled by a control unit near the main exchange. This approach can be considered as a generalization of the principle of centralized control, the network controlled no longer being the network of an exchange but a small local network. Reliability should be ensured by duplication in the central control unit.

The third method consists in deliberately separating a communication network and a control network and in setting each one up independently in accordance with its own economy. Data transmission will link the communication exchanges and the control units so the latter may receive information from subscribers and transmit connection orders. It is precisely this type of structure that will be presented here.

Without pretending that this solution is the best one, it can be shown that a priori it offers enough interesting properties to justify a detailed analysis. An effort will be made to show the attractive aspects of this approach and to present the new problems it raises.

1.1 Principle of the Proposed Structure

There are three major elements in the proposed structure.

(A) A communication network for handling the information to be transmitted for the user. This information or communication traffic can be: telephone traffic, telegraph traffic, data transmission, facsimile, et cetera (with the exception, in principle, of control or management data traffic). This network is composed of switching centers of varied complexity and of the links between these centers.

(B) A computer network composed of computers for the control and management of the communication network and of links to provide for the necessary interchange of information among the computers.

(C) A remote-control network consisting of data links connecting the computers with the various communication centers they control to transfer data and orders in both directions. This network also includes the necessary terminal equipment.

This distinction of three types of networks does not mean that they are completely independent nor that this differentiation is very rigid. Thus, for example, the links of the computer or remote-control networks can be partially or totally constituted by some fixed or variable links of the communication network. Thus the communication network could handle some of the control traffic and, conversely, the computer or remote-control networks could handle some

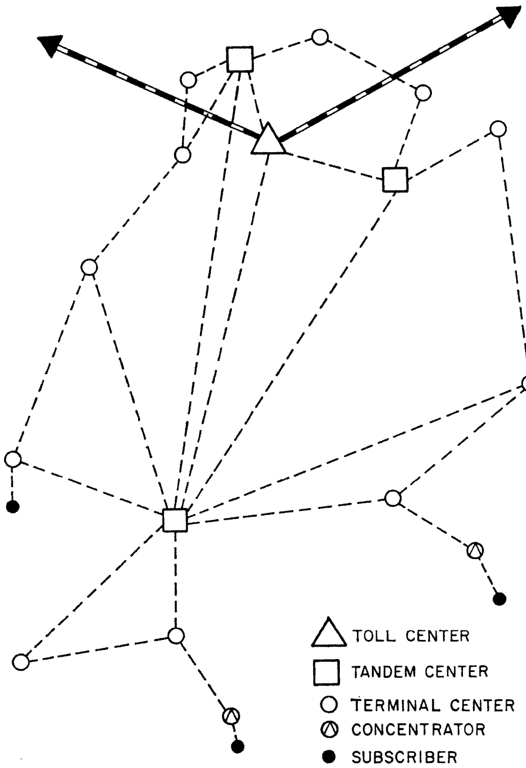

Figure 1—Communication network.

communication messages. Further, some control functions can be transferred from the computers to specialized equipment located in each switching center.

Part of the communication network of a large urban and suburban area is represented in Figure 1. It includes conventional hierarchy of switching centers (concentrators, terminal centers, mixed or pure tandem centers, and a toll center). The proposed network structure will permit independent optimization of this network, taking into account the economic factors specific to transmission and to switching and the interrelation of these factors.

In Figure 2, a network of computers can be seen. They are tightly connected to each other and thus constitute a processing force that can be expanded rapidly to meet the control needs of any part of the network. A two-level hierarchy has also been assumed for these computers. The number of computer levels and the allocation of the functions among them are significant. However, it is clear that the ratio between the number of exchanges and the number of computers should take into account various parameters including the cost of data transmission, the vulnerability to service interruption, the gain due to centralization, and, possibly, the requirements other than telecommunication to be satisfied by the computer network (hospital or meteorological documentation for instance, technical computations, and others).

Figure 3 shows the remote-control network with each exchange connected to 2 different computers situated in different places. Only concentrators have been connected to a single computer. It is clear that only an analysis of the reliability of computers and data links will permit defining the number of links actually necessary for each size and type of exchange.

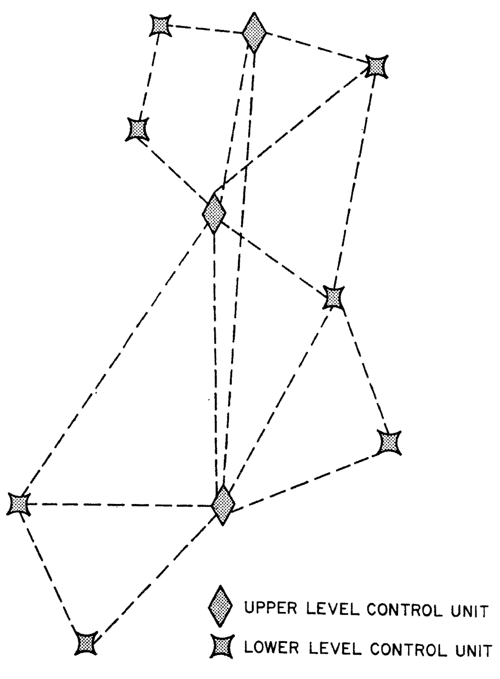

Figure 2—Control network of computers in two levels.

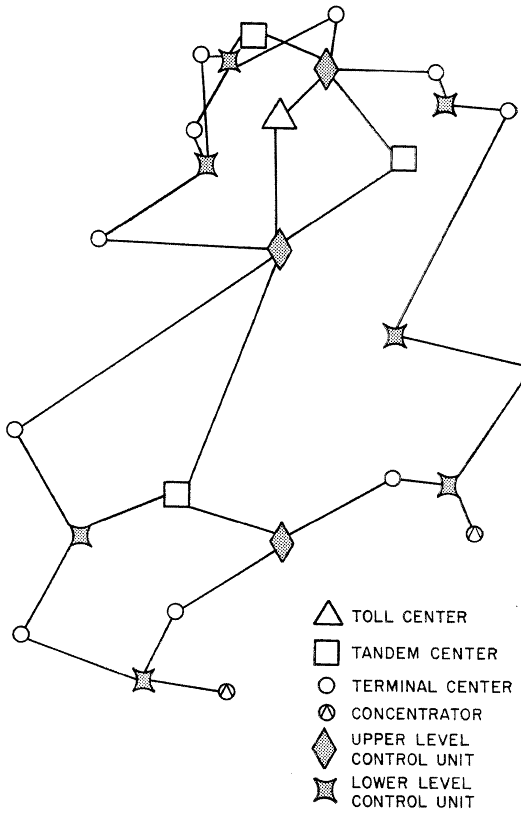

Figure 3—Remote-control network.

Figure 4 shows the whole telecommunication network and is a superposition of the three previous figures.

1.2 Value of the Proposed Structure

1.2.1 *Flexibility*

It is clearly evident that the notion of "telephone system" is changing very rapidly from its old meaning toward a much wider and dynamic conception. Electromechanical systems are being superseded by others based on electronic techniques and it is necessary to take into account the rapid advances being made in the character of these techniques. A telephone system is characterized not only by equipment and circuits but by a method of operation that must be adaptable to changes in the hardware and in the needs of the subscribers.

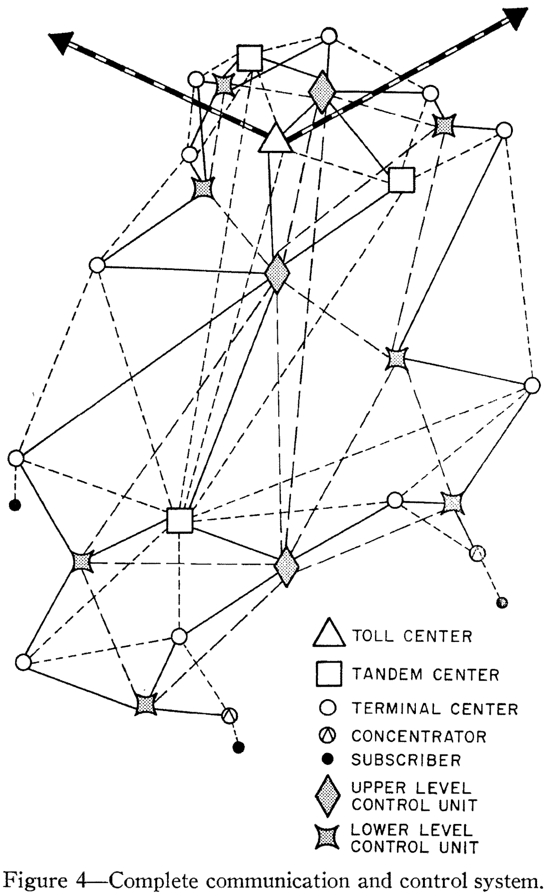

Figure 4—Complete communication and control system.

The proposed structure separates the functions of communication and information processing at the network level rather than within the exchange. This will permit each of these fundamental techniques to evolve independently and without regrettable compromise as soon as the interactions at their interface have been firmly established.

It is clear that such a structure would easily permit passing without serious disturbance from the present systems to semielectronic and then to entirely electronic systems, since the compatibility problems would be solved once and for all by the adoption of a *unique* control method. This transition would not require solutions to all the difficulties at a single time. For instance, the computer network could benefit on a continuing basis from improvements related to its own technique.

1.2.2 *Distributed Redundancy*

The proposed structure permits a major reduction of the amount of redundancy necessary to ensure the reliability of the control units.

If computers can be connected together economically by data links having sufficient speed and capacity, in case of failure any computer can be replaced by its neighbors. It suffices that the processing power of the whole of the computer network be slightly higher than necessary for peak traffic conditions. If the size of the network is only sufficient, the result of a failure will be spread and produce only a small decrease in service over the whole of the network rather than a major interruption over a part of the network. Computers and programs would no longer need major redundancy; only some information relating to each exchange would be stored in memories in two places.

Moreover, as a single computer controls several exchanges, the control programs of these exchanges will be identical or nearly so. This results in a very significant decrease of the total required memory compared with the classical solution in which each exchange is provided with two computers, each with its own copy of the control program.

1.2.3 *Separation of Investments*

In addition to the economic advantages outlined in the previous section, it should be noted that the proposed structure permits practically independent extension of the two fundamental networks. It is clear that the traffic of the control network will be increased only in a relatively slight way by putting into service a new exchange if the size of the network is already large enough and if the transmission of information through the computer network is not limited.

This relative independence between investing in the communication network and in the control network greatly simplifies investment programs since overall quality of service can be balanced against additional profit-earning connections.

The use by the telephone network of only part of the time of a general-purpose information processing network set up on a city or national scale provides it with the service of a larger and faster operating computer than can be justified economically if each exchange were to have its own exclusive computer.

2. General Model

2.1 Communication Network

The great inherent flexibility of a dispersed telecommunication network enables the communication network itself to be more flexible than a network of conventional type. This flexibility will be evident not only in switching but in transmission and in call routing.

2.1.1 *Switching*

A great advantage is the possibility of coordinating different switching systems at the level of the control and management computers. The switching will therefore be carried out as required by either electromechanical switches of the semielectronic systems or by time- or space-division electronic switches of the completely electronic systems. Thus future switching methods may be progressively introduced into the dispersed network after suitable study of their special requirements.

Most of the existing networks are rigorously hierarchical as regards the functions that switching centers can fulfil (local centers or transit centers of different levels). Such hierarchy seems necessary to some extent if only, for example, for forming, after mixing and possibly concentration, the long-distance circuit groups that are sufficiently large to require that their efficiency be as high as possible. A dispersed system should permit introducing some flexibility into this hierarchy to improve reliability and efficiency of the installations.

In the local network of Figure 5, each of the 4 switching levels or planes that can be distinguished corresponds to a different kind of traffic.

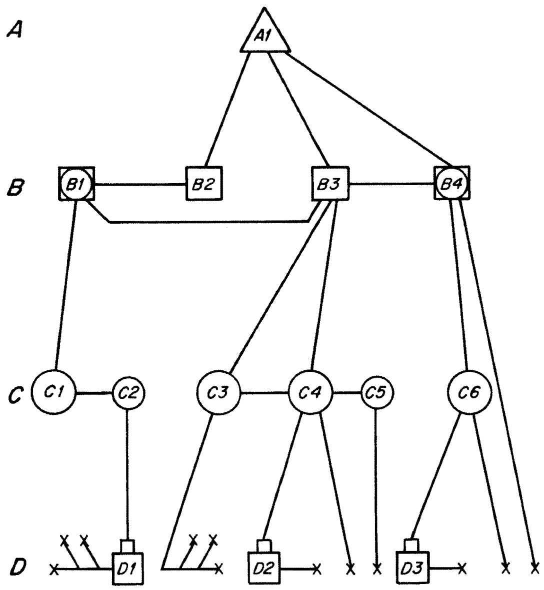

Figure 5—Communication network of 4 switching levels or planes, A through D.

2.1.1.1 *Subscriber and Concentration Plane*

Plane D of Figure 5 includes subscriber installations such as single lines, party lines for two or more subscribers, and private automatic exchanges with one or more lines. It also includes elementary switching devices such as concentrators and remote line-selection units. These devices provide only for concentrating subscriber traffic to centers of a higher plane and cannot set up a connection between two subscribers.

2.1.1.2 *Local Centers Plane*

Plane C of Figure 5 involves switching centers (local or satellite) that enable connections to be set up between subscriber lines (concentrator) and one or more groups of incoming trunks (links) and one or more groups of outgoing trunks (links). As it is not possible to connect an incoming trunk to an outgoing trunk, no transit traffic can be handled in this plane.

2.1.1.3 *Local Transit Centers Plane*

Switching centers in plane B of Figure 5 provide for the transit function, that is, connection of incoming trunks to outgoing trunks. They may also serve subscriber lines directly or through concentrators. Although they are intended to handle local transit traffic they may also handle part of the transit traffic toward other neighboring areas.

2.1.1.4 *Toll Transit Centers Plane*

In the long-distance plane A of Figure 5 the essential function is to handle the traffic between the area in which the centers are and other areas. In the same way that part of this function can be handled by some centers of plane B, the centers of plane A can carry out some of the functions of the centers of planes B and C.

To allocate a center to a plane, the highest level function it can perform is the determinant. In increasing level order these functions are: concentration without local traffic, local traffic without transit, local transit traffic, and toll or long-distance transit traffic.

2.1.2 *Transmission*

Transmission within this network may be of different types: subscriber lines, concentrator lines, simple junctions, and multiplex junctions with frequency division (carrier systems) or time division (pulse code modulation). Rather than considering this diversity as a constraint, the best possible advantage should be obtained from it, from the point of view of flexibility and economy.

As far as the number and size of the different links are concerned, the basic principle will be to provide economically at least 2 paths for going from one point to another of the network, thus ensuring reliability and flexibility of call routing.

The distant units of the concentrators of the D plane are connected to an exchange of one of the higher planes. If economically feasible such units could be joined to the nearest two exchanges.

The C-plane exchanges are either terminal centers or satellites with a single incoming-outgoing direction toward an A- or B-plane exchange. The terminal centers will be connected to at least one of the higher plane exchanges since no transit traffic is possible in the C plane. Each C-plane exchange could also be connected to one or several exchanges of the same plane by direct links, these links being provided exclusively for the interconnection of subscribers.

As the local transit traffic is handled in the B plane, these exchanges will be connected to several C-plane exchanges. They will also be connected to at least one of the A-plane exchanges and, possibly, to other exchanges of the neighboring areas. They will obviously be connected to each other by a strongly linked network.

Finally, an A-plane exchange will handle the outgoing traffic from its area as well as the incoming traffic for this area. Traffic with the immediately adjacent areas may also be handled by some lower-plane exchanges.

The linkage of the transmission network will be tightest in the higher planes and very loose in and between the C and D planes. The network interconnecting the B-plane exchanges will be fairly complete and exchanges in the A plane will be fully linked.

2.1.3 *Call Routing*

In call routing the introduction of computers will permit an important improvement in the dispersed network with respect to existing networks, whether electromechanical or electronic.

For call routing the most modern networks use alternate routing, but more-elaborate methods, such as the dynamic strategies [2] offer numerous advantages in a dispersed network. Computers permit relatively easy implementation of dynamic strategies to improve both flexibility and reliability particularly in case of breakdown or overload.

The dynamic strategies imply that each computer likely to carry out path hunting has information of the state of occupancy of the network. Continually updated information on the exact internal state of each exchange or even on the exact number of trunks occupied in each link would result in much too much data traffic. It is possible to be satisfied with an approximate knowledge of the state of occupancy of each link by considering only three or four classes of occupancy for each link. The limit values of these classes can themselves be approximate if some overlapping between two neighboring classes is permitted [3].

2.2 Computer Network

For this study as a whole, the description of the computer network is in fact the presentation of a set of possibilities that should be studied and compared.

2.2.1 *Internal Organization*

The computer network shown in Figure 2 has two levels of computers, a higher level to be identified as H and a lower level L.

The two main characteristics of the computer network are distribution of capability and cooperation both within each level and between the two levels.

Let us assume for example that computer $H1$ controls the $B1$ and $B2$ centers. If $H1$ fails, computers $H2$ and $H3$ can take over the control of the $B1$ and $B2$ centers, respectively, in addition to their normal load.

There may be a sharing of capabilities among computers in the same plane. For example, the routing tables may be centralized in some computers of the plane, which then receive requests for routing information from the others. It is obviously necessary to estimate the amount of traffic to be handled by the links between computers. It is also necessary to consider the permanent storage of the control programs. In case of difficulty, it may be necessary to reload the programs in a memory. These programs can be stored on magnetic tape but it is not necessary to equip each computer with tape units. These units can be connected to some computers, and the programs to be reloaded will then be transmitted to the other computers through high-speed data links. The modifications or the updating of the programs and tables will therefore be carried out by only some installations.

There is also sharing of capabilities and cooperation among the planes. The H computers carry out some special functions such as the control of the exchanges of the A and B planes, or the implementation of routing strategies in the communication network. The H computers cooperate with the L computers to control the exchanges of the C and D planes. Let us consider, for example, a call between two subscribers belonging to $C1$ and $C2$ exchanges and let us assume that the control of $C1$ and $C2$ depends on the $L1$ and $L2$ computers, respectively. Then, the call necessitates the cooperation between *L1, L2,* and a third computer of the *H* plane. This cooperation is made possible through the interconnection of the computer planes.

Figure 6 shows the schematic diagram of a possible interconnection in which each *L* computer is connected to two *H* computers for reliability reasons. Figure 7 shows another arrangement in which each *L* computer is connected to only one *H* computer. Reliability is ensured in this case in that if *H1* fails, *L1* is then connected to *H2* through *L2*. This necessitates fewer transmission paths but more-complex switching.

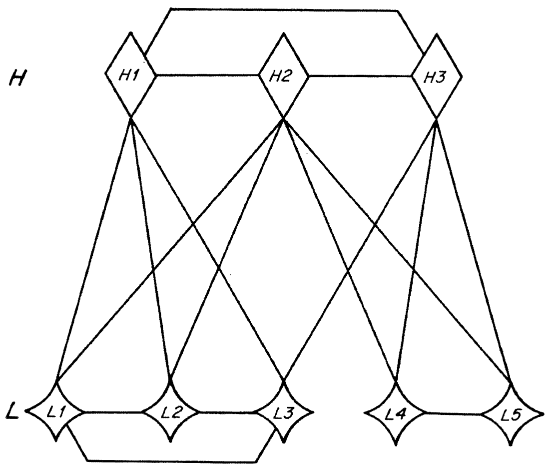

Figure 6—Computer network in which each low-level computer *L* is connected to two high-level computers *H*.

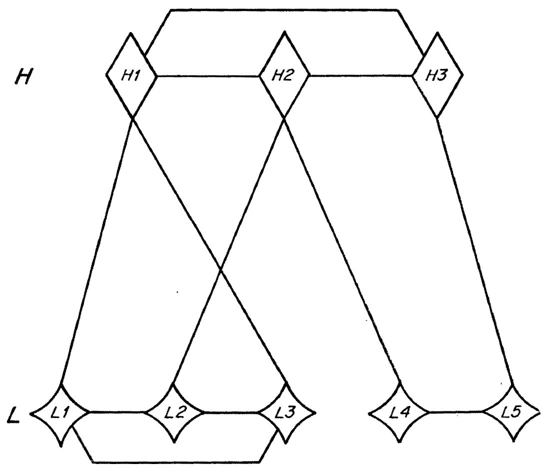

Figure 7—Computer network in which each low-level computer *L* is connected to only one high-level computer *H*. If *H1* fails, *L1* is connected to *H2* via *L2*.

2.2.2 *Interconnection with the Communication Network*

The *H* computers control the *A* and *B* planes. Each *A*- or *B*-plane exchange is connected to two *H* computers.

In Figure 8, *A1* is connected to *H1* and *H2,* and *B3* to *H2* and *H3*. The *L* computers control the *C* and *D* planes. Here again, each exchange is connected to two *L* computers (see Figures 9 and 10) but each concentrator is connected to only a single *L* computer. It is assumed that the concentrators are sufficiently small to tolerate waiting periods longer than those of the terminal exchanges and remote line-selection units.

2.3 Distribution of Functions

The passive link between the communication and computer devices, the remote-control network, can be defined only with respect to them. In particular its design is strongly dependent on the amount of information that it must handle.

Before such an estimate can be made, it is necessary to define the functions assigned to the communication network and to the computers. Also the initial amount of information given by the subscribers can vary substantially.

Information from subscribers passing from the communication network to the computer network is either at the level of the subscribers themselves in a line circuit or at a more-concentrated level: junctor, register, receiver, et cetera.

Various arrangements can be envisaged. However, to simplify the report, it will be assumed that information coming from a subscriber appears as a new call that is detected at the level of an individual circuit associated with the line or as a called number that is detected at a more-concentrated level in a circuit which we shall call a junctor.

Information transmitted from the computer network to the communication network involves two general classes of functions. One class of functions concerns the supervision of the state of the communication network with regard to the changes initiated by subscribers, and the other class concerns the control functions for the establishment of a new state of the communication network such as setting up a new connection.

The functions in the first-mentioned class include scanning of the state of the lines and scanning of the state of the junctors.

The functions in the second class include control of the communication network (connector) possibly including the line circuits (cutoff relays) and control of the junctors associated with the different phases of a call (sending of the different tones, ringing, et cetera).

These are not the only functions but other functions such as the control of individual subscriber meters are neglected as they require relatively little transmission of information.

The scanning and driving circuits constitute the interface equipment between the communication network and the computers; their numerous technological links with the communication network well justify their being closely associated with the communication network.

2.4 Remote-Control Network

2.4.1 *Introduction*

The expected advantages of a dispersed network of the type considered result from, among others, the relative independence of the location and extent of the communication and computer networks.

This independence of the two networks is permissible only if the remote-control network that interconnects them represents a small fraction

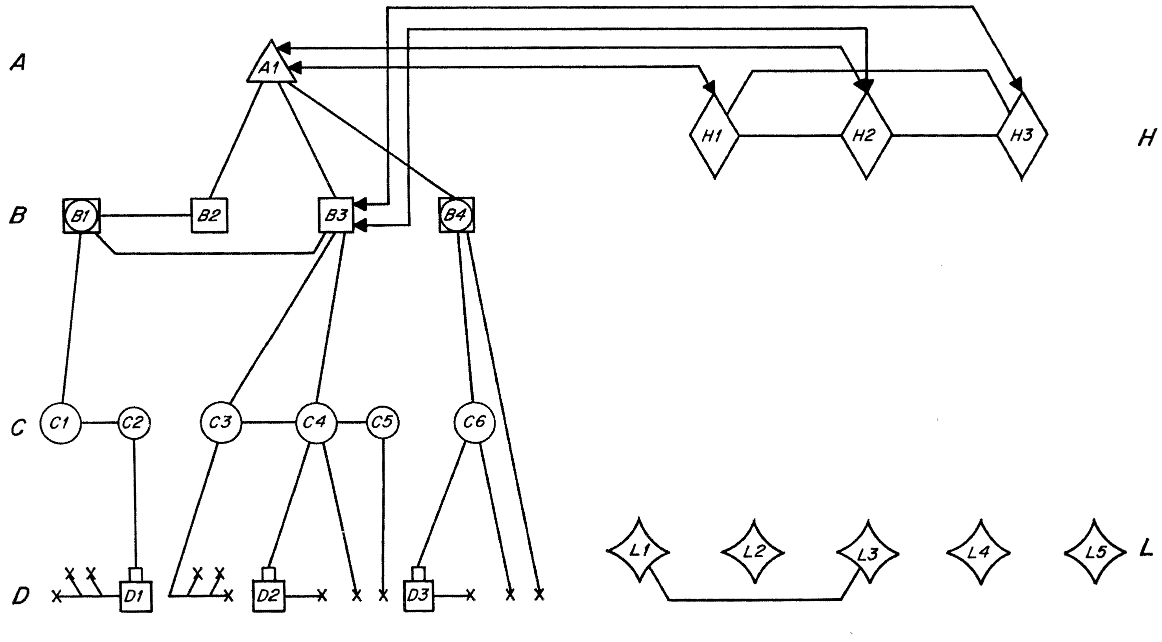

Figure 8—Control of A- and B-plane switching centers.

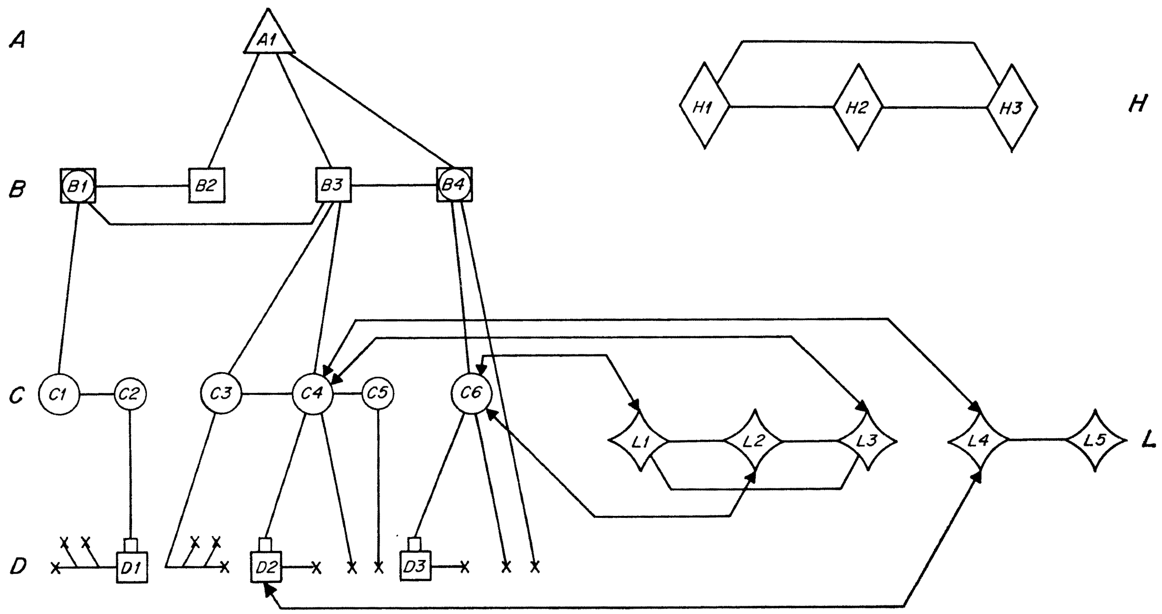

Figure 9—Control of C- and D-plane switching centers.

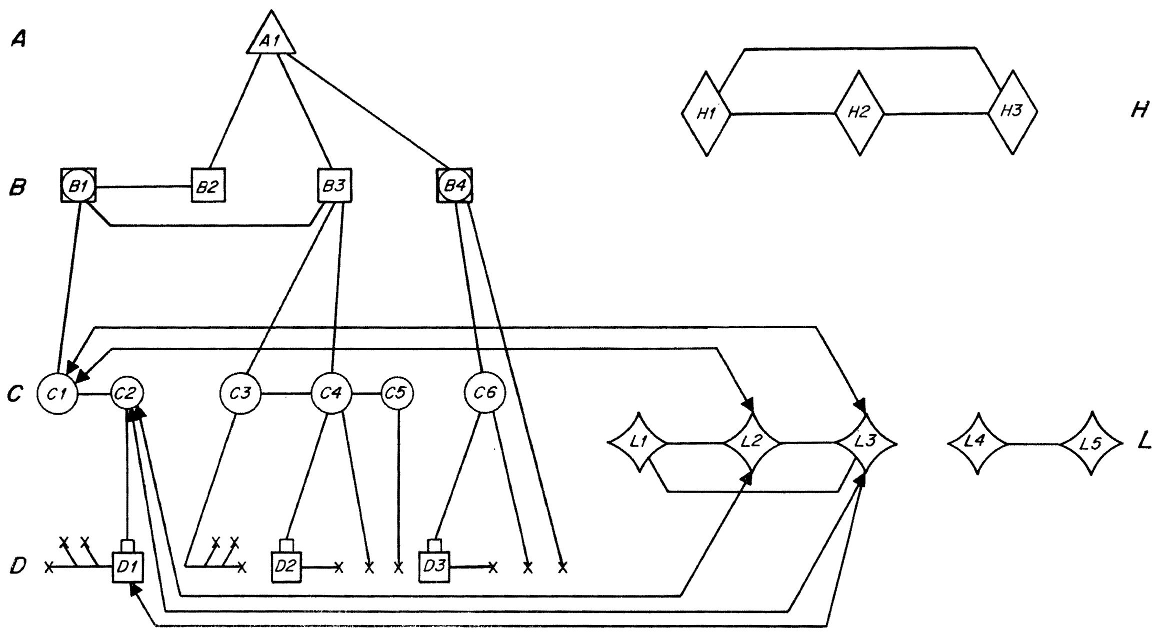

Figure 10—Alternative form of control of C- and D-plane switching centers.

of their costs. This can be called the fundamental hypothesis.

To verify this idea, a further economic study is necessary as a conclusion to the technical study.

However, to support this fundamental hypothesis, a first approach consists in estimating, even rather approximately, the flow of information between the communication network and the computers. If this information flow is small, it would be reasonable to assume that the initial hypothesis is valid.

2.4.2 *Estimation of Remote-Control Network Traffic*

2.4.2.1 *Basic Traffic in the Communication Network*

To estimate the traffic in the remote-control network, it is necessary to know the communication traffic; the usually adopted mean value of 0.1 erlang (originating and terminating) per subscriber will be chosen, that is, 4.15 calls per second for 10 000 subscribers with an average holding time of 2 minutes. In what follows, the quantities of information will be given in bits per second for 10 000 subscribers and also in bits per second per subscriber.

2.4.2.2 *Traffic from Communication Network Toward Computer*

In line scanning, a line can present two states corresponding to the on- or off-hook positions of the handset. It is assumed that an average period of 1 second elapses from the picking up of the handset to the moment when the line becomes isolated from the scanning circuit and that each line is scanned 4 times per second. This signifies that information that a line is activated to make a call will appear 16.6 times per second. By assuming that the transmitted information is the code of the line supplied in binary-coded-decimal form (16 bits), approximately 300 bits will be transmitted per second for 10 000 lines.

It must be noted that the information transmitted is the identity of a new calling line repeated 4 successive times. If supplementary means to identify the previous state of a line are associated with the scanning circuit, the preceding information traffic is then divided by 4.

The essential part of the information transmitted from the junctors comes from subscribers' dialling into the junctors.

In the estimate that follows it is assumed that the information is received pulse by pulse without digit reconstitution in the junctor. If 7-digit numbering is assumed, 38.5 pulses will be received on the average in the junctor for each dialling from a subscriber.

In addition, if it is assumed that the junctors are scanned every 10 milliseconds and that the openings of the subscriber loop are read, the total number of readouts is 1120 per second for 7-digit numbering. To this information, it is necessary to add that which comes from the incoming calls, which is assumed to have the same form but only 4 digits that have to be taken into account. In addition, if it is assumed that the telephone traffic coming into the exchange represents 80 percent of the traffic originated by subscribers, this corresponds to 512 readouts per second.

Thus, the average number of readouts made in the junctors is about 1630 per second for 10 000 lines.

As the information transmitted is the junctor code, which is in the form of a 10-bit pure binary code, a total of 16 300 bits per second are transmitted to the computers for this function in the case of a 10 000-line exchange.

2.4.2.3 *Traffic from Computer Network Toward Communication Network*

Control of the communication network: For a total traffic of 0.1 erlang per subscriber, the distribution of which is 20 percent local, 40 percent incoming, and 40 percent outgoing traffic, the different control operations are approximately 1 local connection order per second, 4 outgoing connection orders per second, and 4 incoming connection orders per second.

We shall not count release orders since it can be assumed that they are accomplished when new connections are established without any supplementary seizing of the control device. This procedure assumes therefore that the state of occupancy of the connection network is known by a means outside the network (for example in memory).

It is assumed that a 50-bit code is necessary to define an incoming or outgoing connection and a 30-bit code to define a local connection. A total of 300 bits per second for 10 000 subscribers is obtained for the control of the communication network.

For junctor control distinction can be made mainly between the local junctors and the incoming junctors from the point of view of the necessary control information.

For the local junctors as has been pointed out previously, the control consists in distinguishing a certain number of possible states of the junctor, states that are related to the different phases that can be observed during a call. By adopting 16 different possible states and by assuming that these 16 states are encountered during a local call, it is necessary to transmit the junctor code of 10 bits plus 4 bits characterizing the state or 224 bits.

Therefore, 224 bits per second for 10 000 subscribers are necessary for local junctors.

For outgoing junctors 8 possible states can be considered plus the sending to the distant office of dialling pulses of the called number, having an average of 38.5 pulses per call. Taking into account all this traffic gives 600 bits per second.

Total information flow for junctor control including incoming junctors amounts to 1000 bits per second for 10 000 subscribers.

2.4.2.4 *Results of Estimates*

Traffic from the communication network to the computer network totals 16 600 bits per second for 10 000 subscribers or 1.66 bits per subscriber per second.

Traffic from the computer network to the communication network is 1300 bits per second for 10 000 subscribers or 0.13 bit per subscriber per second.

Although these figures are approximate estimates, they show that the information traffic is compatible with present-day means for data transmission.

2.5 Traffic Between Computers

As the system requires that computers be capable of replacing each other, it is necessary to provide for information interchange between two computers connected to the same exchange so as to keep both updated.

This shared information may be reduced to that of the calls already established in the speech network, so that in the case of a fault of the normal processing computer, the other is able at least to control the release of the connected paths.

A computation similar to the one carried out for information interchange between computers and exchanges gives a traffic of 0.1 bit per second per subscriber.

3. Conclusion

The dispersed structure of a telecommunication network that has been presented is not the result of a long and thorough study. However it is based on experience acquired in the development of central-control telecommunication systems and can be a starting point for a new study of a general organization of telecommunication networks.

From the economic point of view it is certainly beneficial to use in each part of a network the most suitable switching or transmission techniques. The proposed structure permits simple and economical adaptation and coexistence of various techniques within a large-area network including the introduction of new techniques as they are developed. The structure and organization of the network can be homogeneous while the techniques used for implementation are heterogeneous.

Regardless of the economic advantages this adaptation flexibility can justify for itself further research.

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Pierre Sénèque was born in Paris, France, on 17 August 1927. In 1950 he obtained an engineering diploma from the École Supérieure d'Électricité de Paris.

He came to Laboratoire Central de Télécommunications in 1951 and participated in studies of electronic switching. He became head of the Advanced Technologies Group, which is part of the Research on Telephone Systems Department. In January 1967 he joined Compagnie Générale de Constructions Téléphoniques in the Switching Division of the Technical Department.

Schalter und Tasten (Reference Data for Switches and Push Buttons)

This German language data book on switches and push buttons is arranged to aid the designer in finding the device most suited for his need. The introduction gives a comprehensive survey of contact materials and shapes, such as: bridging, knife-blade, and spoon. The main part deals with numerous types of switches, including single and ganged units in standard, miniature, and microswitch sizes. All types are fully described both electrically and mechanically, including dimensional drawings.

This handbook is 15 by 21 centimeters (5.9 by 8.3 inches) and can be ordered from SEL Kontakt-Bauelemente, 3 Giessereistrasse, Nürnberg, Germany.

Propagation in Periodically Deformed Circular and Rectangular Waveguides*

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1. Introduction

The traveling-wave tube is a device for transferring the energy from a stream of electrons to an electromagnetic field. A traveling-wave amplifier, in particular, consists essentially of two ingredients, namely, the electron stream and a waveguide capable of propagating fields at phase velocities equal to achievable stream velocities. Further, if the amplifier is to be capable of producing high average powers, then its slow-wave guide must be a relatively massive structure to accommodate such power levels. (For further discussion of the special problems met in the development of such tubes, we refer the reader to the monograph of J. F. Gittins [17].)

The consideration last mentioned thus makes slow-wave circuits derived from simple circular and rectangular waveguide attractive *a priori* for such an application. In this paper, we give the theory of propagation in two such types of guide. Our aim in this work is not to provide design criteria but to obtain the expressions needful in the generation of such criteria. In any event, the latter must always be developed on an experimental and empirical basis as well as from theoretical considerations. (The reader interested solely in the conclusions drawn from our analysis may confine his attention to Sections 4 and 6 below.)

In the course of this work, it was realized that our method of analysis of axially corrugated circular guide is applicable to the study of propagation in any closed waveguide whose bounding wall is a sufficiently smooth surface of revolution. For that reason, our analysis of this guide—which thus exhibits the method on a simple model—is given in some detail.

* This paper is based in part on work originally performed under General Development Case 0052 of ITT Federal Laboratories.

2. Fundamental Formulas. Field Vectors and Potentials

For completeness and ease of reference, we collect here some of the formulas and equations of the theory of electromagnetic fields. We employ meter-kilogram-second (MKS) units exclusively. (For a complete discussion of these expressions, in meter-kilogram-second units, we refer to such texts as Stratton [1], Schelkunoff [2], Slater [3], and Hund [4]. We follow here the notation and terminology of Stratton.)

Maxwell's equations for the interior of a vacuous region Δ bounded by a perfectly conducting wall Λ are ([1])

$$\nabla \times \mathbf{H} = \epsilon \frac{\partial \mathbf{E}}{\partial t}, \quad \nabla \times \mathbf{E} = - \mu \frac{\partial \mathbf{H}}{\partial t}$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic intensities, and ϵ and μ are the permittivity and permeability of vacuum, respectively. Let $\mathbf{N}$ be the unit normal to Λ; at points of Λ, we have

$$\mathbf{N} \times \mathbf{E} = 0, \quad \mathbf{N} \times \mathbf{H} = \mathbf{K}$$

where $\mathbf{K}$ is the surface current density on Λ. Associated with $\mathbf{K}$ is the surface charge density δ, which, together with $\mathbf{K}$, must satisfy a conservation equation at points of Λ. In terms of these densities, the vector and scalar potentials of the field $\mathbf{A}$ and Φ, respectively, are given by the following surface integrals over Λ.

$$\mathbf{A}(P, t) = \frac{\mu}{4\pi} \int\int_{\Lambda} \frac{\mathbf{K}(Q, t^*)}{R} da,$$
$$\Phi(P, t) = \frac{1}{4\pi\epsilon} \int\int_{\Lambda} \frac{\delta(Q, t^*)}{R} da. \tag{1}$$

In (1), P is an arbitrary interior point of Δ and Q is an arbitrary point of the surface Λ; R is the distance from P to Q; $t^* = t - R/c$, where c is the velocity of light in vacuum. In terms of the potentials (1), the field vectors

E and **H** are given by

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}, \quad \mu\mathbf{H} = \nabla \times \mathbf{A}. \tag{2}$$

3. Propagation in Axially Corrugated Waveguide

We first study propagation in a guide of circular cross section, whose (perfectly conducting) wall is the oscillating surface Σ of revolution having the equation

$$r = a + B \sin \frac{2\pi}{L} z, \quad 0 < B < a$$

in cylindrical coordinates r, φ, z. Figure 1A is a sketch of a portion of Σ, showing its disposition relative to rectangular and cylindrical coordinates, and Figure 1B represents an arbitrary axial section. (For obvious reasons, we have designated Σ as *axially corrugated waveguide.*) To distinguish between points on the surface Σ and points in the interior, let θ and ζ be angular and axial parameters of position on Σ and let r, φ, z denote the cylindrical coordinates of any point not on, but interior, to Σ. Then the position vector **X** to an arbitrary point on Σ is given by

$$\Sigma : \mathbf{X} = (\rho \cos\theta, \rho \sin\theta, \zeta),$$
$$\rho = a + B \sin \frac{2\pi}{L}\zeta \tag{3}$$

while

$$\mathbf{Y} = (r\cos\varphi, r \sin\varphi, z) \tag{4}$$

is the vector to an arbitrary interior point.

We must now calculate some expressions concerning the geometry of Σ—area element, unit vectors, and so on. First,

$$\mathbf{X}_\zeta = \left(\frac{2\pi B}{L}\cos\frac{2\pi}{L}\zeta\cos\theta, \frac{2\pi B}{L}\cos\frac{2\pi}{L}\zeta\sin\theta, 1\right)$$

where $\mathbf{X}_\zeta = \partial\mathbf{X}/\partial\zeta$

$$\mathbf{X}_\theta = (-\rho\sin\theta, \rho\cos\theta, 0).$$

Then, letting $\sigma = 2\pi B/L$, we have

$$E = \mathbf{X}_\zeta \cdot \mathbf{X}_\zeta = 1 + \sigma^2 \cos^2 \frac{2\pi}{L}\zeta,$$
$$F = \mathbf{X}_\zeta \cdot \mathbf{X}_\theta = 0,$$
$$G = \mathbf{X}_\theta \cdot \mathbf{X}_\theta = \rho^2.$$

Then the element of area da on Σ is given by [5]

$$da = (EG - F^2)^{1/2} d\zeta d\theta = \left(a + B\sin\frac{2\pi}{L}\zeta\right) \times \left(1 + \sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2} d\zeta d\theta. \tag{5}$$

The unit vectors $\mathbf{i}_\zeta$ and $\mathbf{i}_\theta$ along the parametric curves on Σ are

$$\mathbf{i}_\zeta = \frac{\mathbf{X}_\zeta}{|\mathbf{X}_\zeta|} = \frac{\left(\sigma\cos\frac{2\pi}{L}\zeta\cos\theta, \sigma\cos\frac{2\pi}{L}\zeta\sin\theta, 1\right)}{\left(1 + \sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}} \tag{6}$$

1A

1B

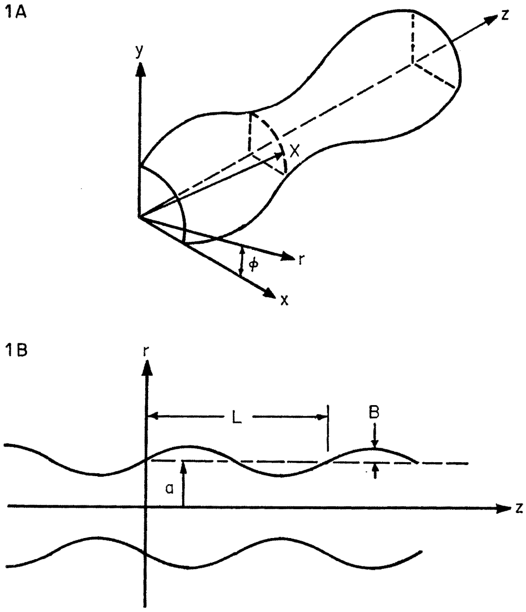

Figure 1—A. Sketch of the portion in the first octant of the surface of revolution Σ, whose equation in cylindrical coordinates r, φ, z is $r = a + B\sin\frac{2\pi}{L}z$, $0 < B < a$. **X** represents the position vector to an arbitrary point of Σ. B. Sketch of the graph of an arbitrary section through the axis of revolution of the surface Σ; a = mean radius, B = depth of the corrugation, L = period.

$$\mathbf{i}_\theta = \frac{\mathbf{X}_\theta}{|\mathbf{X}_\theta|} = (-\sin\theta, \cos\theta, 0). \tag{7}$$

The unit vectors $\mathbf{i}_r$, $\mathbf{i}_\varphi$, $\mathbf{i}_z$ at an arbitrary but fixed point in the interior of Σ (to which $\mathbf{Y}$ is the position vector) are

$$\mathbf{i}_r = (\cos\varphi, \sin\varphi, 0),$$
$$\mathbf{i}_\varphi = (-\sin\varphi, \cos\varphi, 0), \quad \mathbf{i}_z = (0, 0, 1). \tag{8}$$

When $\mathbf{i}_\zeta$ of (6) is expressed in terms of the unit vectors (8), we have

$$\mathbf{i}_\zeta = \frac{\mathbf{i}_r\sigma\cos\frac{2\pi}{L}\zeta\cos(\theta-\varphi) + \mathbf{i}_\varphi\sigma\cos\frac{2\pi}{L}\zeta\sin(\theta-\varphi) + \mathbf{i}_z}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\right)^{1/2}}. \tag{9}$$

The distance R between any point of Σ and an arbitrary but fixed point in the interior of Σ is

$$\begin{aligned} R^2 &= |\mathbf{X} - \mathbf{Y}|^2 \\ &= r^2 + \rho^2 - 2r\rho\cos(\varphi - \theta) \\ &\qquad + (\zeta - z)^2, \\ \rho &= a + B\sin\frac{2\pi}{L}\zeta. \end{aligned} \tag{10}$$

The arc-length $s = s(\zeta)$, measured along an arbitrary generating curve of Σ, is given by

$$\begin{aligned} s &= \int_0^\zeta (\mathbf{X}_\zeta\cdot\mathbf{X}_\zeta)^{1/2}d\zeta \\ &= \int_0^\zeta \left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2} d\zeta \\ &= \frac{L}{2\pi}(1+\sigma^2)^{1/2}\int_0^{2\pi\zeta/L}(1-l^2\sin^2 x)^{1/2}dx \end{aligned} \tag{11}$$

where, in (11), $l = \sigma/(1+\sigma^2)^{1/2}$. We require, finally, the surface divergence operator ∇_Σ on Σ, defined by

$$\nabla_\Sigma = \frac{\mathbf{X}_\theta \times \mathbf{N}\frac{\partial}{\partial\zeta} + \mathbf{N}\times\mathbf{X}_\zeta\frac{\partial}{\partial\theta}}{\mathbf{X}_\zeta\times\mathbf{X}_\theta\cdot\mathbf{N}} \tag{12}$$

where $\mathbf{N}$ is the unit normal to Σ. Carrying out the indicated calculations in (12), we obtain the formulas

$$\begin{aligned} \nabla_\Sigma &= \mathbf{i}_\zeta \frac{1}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}}\frac{\partial}{\partial\zeta} \\ &\qquad + \mathbf{i}_\theta\frac{1}{a + B\sin\frac{2\pi}{L}\zeta}\frac{\partial}{\partial\theta} \\ &= \mathbf{i}_\zeta\frac{\partial}{\partial s} + \mathbf{i}_\theta\frac{1}{a+B\sin\frac{2\pi}{L}\zeta}\frac{\partial}{\partial\theta}. \end{aligned} \tag{13}$$

Suppose now that the guide whose boundary is the periodic surface Σ extends indefinitely in both directions of the z axis, and consider the problem of finding the modes of propagation in such a guide, corresponding to some arbitrary frequency f (cycles per second). We can assume that all field vectors, potentials, and densities depend on the time in the form $e^{-i\omega t}$ ($\omega = 2\pi f$). The potential integrals (1) now take the form

$$\begin{aligned} \mathbf{A}(P_1) &= \frac{\mu}{4\pi}\int\int_\Sigma \frac{e^{ikR}}{R}\mathbf{K}(P_2)da, \\ \Phi(P_1) &= \frac{1}{4\pi\epsilon}\int\int_\Sigma\frac{e^{ikR}}{R}\delta(P_2)da \end{aligned} \tag{14}$$

where $k = \omega/c$ and R is given by (10). (In (14), the arguments P_1 and P_2 refer to fixed and variable points in the interior of Σ and on Σ, respectively.) The densities $\mathbf{K}$ and δ (see Section 2) must satisfy on Σ the equation of conservation

$$\nabla_\Sigma\cdot\mathbf{K} = i\omega\delta. \tag{15}$$

If, in (14), $\mathbf{K}$ and δ are the densities on Σ associated with a mode of propagation in the guide, then the corresponding fields $\mathbf{E}$ and $\mathbf{H}$ follow at once from the potentials *via* (2), which now take the form

$$\mathbf{E} = -\nabla\Phi + i\omega\mathbf{A}, \quad \mu\mathbf{H} = \nabla \times \mathbf{A}. \quad (16)$$

Of course, we do not yet know these densities. However, if one can obtain suitable *approximate* densities, then the corresponding *approximate* fields also follow from (14) and (16). Our method consists in just such employment of proper approximate densities. (However, due to the fact that Σ is a surface of revolution, it is possible to show that our method is capable of yielding the correct densities.)

Approximate formulas for the required surface densities may be obtained from the well-known modes of propagation in straight circular waveguide ($B = 0$). For, as the depth B of the corrugation tends to zero, a mode of propagation in the periodic guide must tend continuously to a known mode of propagation in straight guide. Conversely, it is reasonable to assume that, for sufficiently small values of B/a and for values of the period L small compared with a half wavelength, the densities $\mathbf{K}$ and δ for the periodic guide differ little from their limiting values as $B \to 0$. From among all possible such modes, we shall now deduce approximate densities which, as $B \to 0$, tend to the densities associated with the lowest-order E-wave in the straight guide (TM_{10} mode).

The components of the field vectors for the TM_{10} mode in straight circular guide are well known (see, for example, [2], [4], and [24]). The corresponding surface current density $\mathbf{K}$ has only an axial component $\mathbf{i}_z K_z$ given by

$$K_z = \frac{i\omega\epsilon E_0}{\gamma} J_1(\gamma a) e^{i\beta z} \quad (17\text{A})$$

where

$\gamma^2 = k^2 - \beta^2 = (x_0/a)^2$
x_0 = smallest positive zero of

$$J_0(x) = 2.405 \quad (17\text{B})$$

and E_0 is an arbitrary constant. An approximate current density for the corresponding mode in our periodic guide is now obtained from (17A) by interpreting a as the mean radius, and by replacing axial distance z along the straight guide by the distance $s = s(\zeta)$ along the periodic guide. Thus, we have $\mathbf{K} = \mathbf{i}_\zeta K_\zeta$, with

$$K_\zeta = \frac{i\omega\epsilon E_0}{\gamma} J_1(\gamma a) e^{i\beta s(\zeta)} \quad (18)$$

and, since (18) is independent of θ, (13) gives the associated surface charge density

$$\delta = \frac{i\beta\epsilon E_0}{\gamma} J_1(\gamma a) e^{i\beta s(\zeta)}. \quad (19)$$

We now substitute $\mathbf{i}_\zeta$, K_ζ, and δ of (18) and (19) into the potential integrals (14), along with the formula (5) for da. First, using the expression (9) for $\mathbf{i}_\zeta$, we have

$$\mathbf{A} = \frac{i\omega\mu\epsilon E_0\sigma}{4\pi\gamma} J_1(\gamma a) \times \int\!\!\int_\Sigma \frac{e^{ikR}}{R} \left[\mathbf{i}_r \cos\frac{2\pi}{L}\zeta \cos(\theta - \varphi) + \mathbf{i}_\varphi \cos\frac{2\pi}{L}\zeta \sin(\theta - \varphi) + \mathbf{i}_z\right] da$$

from which we have $\mathbf{A}$ resolved into its cylindrical components. Hence

$$A_r = \frac{i\omega\mu\epsilon E_0\sigma a}{4\pi\gamma} \times J_1(\gamma a) \int_0^{2\pi} \cos(\theta - \varphi) d\theta \times \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta s(\zeta)} \cos\frac{2\pi}{L}\zeta \times \left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right) d\zeta \quad (20\text{A})$$

$$A_\varphi = \frac{i\omega\mu\epsilon E_0\sigma a}{4\pi\gamma} \times J_1(\gamma a) \int_0^{2\pi} \sin(\theta - \varphi) d\theta \times \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta s(\zeta)} \cos\frac{2\pi}{L}\zeta \times \left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right) d\zeta \quad (20\text{B})$$

$$A_z = \frac{i\omega\mu\epsilon E_0 a}{4\pi\gamma} J_1(\gamma a) \times \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta s(\zeta)} \times \left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right) d\zeta \quad (20C)$$

$$\Phi = \frac{i\beta E_0 a(1+\sigma^2)^{1/2}}{4\pi\gamma} J_1(\gamma a) \times \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta s(\zeta)} \times \left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right) \times \left(1 - l^2 \sin^2\frac{2\pi}{L}\zeta\right)^{1/2} d\zeta \quad (20D)$$

where the distance R is given by (10). Our task now is to evaluate the integrals (20) without further simplifying assumptions, that is, taking the geometry of the guide into account exactly.

Let us notice first that (20B) vanishes identically (as we should expect for an angularly independent surface distribution), since the integrand of (20B)—regarded as a function of θ—is odd and periodic with period 2π.

Turning to the remaining integrals (20), each contains the phase factor $\exp[i\beta s(\zeta)]$, where the arc-length function $s(\zeta)$ is given by (11). Let a_0 be the average value of the integrand of (11) over its period π. Then

$$a_0 = \frac{2}{\pi}\int_0^{\pi/2} (1 - l^2 \sin^2 x)^{1/2} dx = \frac{2}{\pi} E(l)$$

where $E(l)$ is the complete elliptic integral of the second kind [6]. Let

$$a(x) = (1 - l^2 \sin^2 x)^{1/2} - a_0;$$

then

$$s(\zeta) = \frac{L}{2\pi}(1+\sigma^2)^{1/2} \int_0^{(2\pi/L)\zeta} [a_0 + a(x)] dx = \frac{2}{\pi} E(l)(1+\sigma^2)^{1/2}\zeta + A(\zeta)$$

where

$$A(\zeta) = \frac{L}{2\pi}(1+\sigma^2)^{1/2} \int_0^{(2\pi/L)\zeta} a(x) dx.$$

Also let

$$\beta_0 = \frac{2}{\pi} E(l)(1+\sigma^2)^{1/2}\beta. \quad (21)$$

Then

$$e^{i\beta s(\zeta)} = e^{i\beta_0\zeta} e^{i\beta A(\zeta)}.$$

Since $a(x)$ is periodic with zero average value, its integral $A(\zeta)$ is also periodic and hence so is $\exp[i\beta A(\zeta)]$. Therefore we have

$$e^{i\beta s(\zeta)} = e^{i\beta_0\zeta} \sum_{-\infty}^{\infty} A_n e^{i(2n\pi/L)\zeta} = \sum_{-\infty}^{\infty} A_n e^{i\beta_n\zeta} \quad (22)$$

where the A_n's are the Fourier coefficients of $\exp[i\beta A(\zeta)]$ and we set

$$\beta_n = \beta_0 + \frac{2n\pi}{L}, \quad n = \pm 1, \pm 2, \cdots \quad (23)$$

Now in (20C), we have

$$e^{i\beta s(\zeta)}\left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right) = \sum_{-\infty}^{\infty} A_n \left[1 - \frac{iB}{2a}\left(e^{i(2\pi\zeta/L)} - e^{-i(2\pi\zeta/L)}\right)\right] e^{i\beta_n\zeta} = \sum_{-\infty}^{\infty} B_n e^{i\beta_n\zeta} \quad (24)$$

where

$$B_n = A_n + \frac{iB}{2a}(A_{n+1} - A_{n-1}), \quad n = 0, \pm 1, \pm 2, \cdots \quad (25)$$

Next, let

$$\left(1 - l^2 \sin^2\frac{2\pi}{L}\zeta\right)^{1/2} = \sum_{-\infty}^{\infty} C_n e^{i(2n\pi/L)\zeta}. \quad (26)$$

Then

$$e^{i\beta s(\zeta)}\left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right)\left(1 - l^2\sin^2\frac{2\pi}{L}\zeta\right)^{1/2} = e^{i\beta_0\zeta}\left(\sum_n B_n e^{i(2n\pi/L)\zeta}\right)\left(\sum_p C_p e^{i(2p\pi/L)\zeta}\right) = \sum_n D_n e^{i\beta_n\zeta} \quad (27)$$

where

$$D_n = \sum_{p=-\infty}^{\infty} B_p C_{n-p}, \quad n = 0, \pm 1, \pm 2, \cdots \tag{28}$$

Finally, for A_r, we have

$$e^{i\zeta s(\zeta)}\left(1 + \frac{B}{a}\sin\frac{2\pi}{L}\zeta\right)\cos\frac{2\pi}{L}\zeta$$

$$= e^{i\beta_0\zeta}\cos\frac{2\pi}{L}\zeta \sum_{n=-\infty}^{\infty} B_n e^{i(2n\pi/L)\zeta}$$

$$= \sum_{n=-\infty}^{\infty} E_n e^{i\beta_n\zeta} \tag{29}$$

where

$$E_n = \tfrac{1}{2}(B_{n+1} + B_{n-1}), \qquad n = 0, \pm 1, \pm 2, \cdots \tag{30}$$

We now substitute the series (24)–(30) into (20), and make the change of variable $\zeta = x + z$. Then (20) becomes, on interchanging orders of summation and integration,

$$A_r = \frac{i\omega\mu\epsilon E_0\sigma a}{4\pi\gamma} J_1(\gamma a) \sum_n E_n e^{i\beta_n z} \times \int_0^{2\pi} \cos(\theta - \varphi) d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta_n x} dx \tag{31A}$$

$$A_z = \frac{i\omega\mu\epsilon E_0 a}{4\pi\gamma} J_1(\gamma a) \sum_n B_n e^{i\beta_n z} \times \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta_n x} dx \tag{31B}$$

$$\Phi = \frac{i\beta E_0 a(1+\sigma^2)^{1/2}}{4\pi\gamma} J_1(\gamma a) \sum_n D_n e^{i\beta_n z} \times \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta_n x} dx \tag{31C}$$

where

$$R = [r^2 + \rho^2 - 2r\rho\cos(\varphi - \theta) + x^2]^{1/2}$$

$$\rho = a + B\sin\frac{2\pi}{L}(x + z). \tag{32}$$

Thus, we have the same integral with respect to x in each of expressions (31) and, indeed, A_z and Φ only differ in the Fourier coefficients B_n and D_n.

To evaluate

$$I_n = \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta_n x} dx \tag{33}$$

we use Sommerfeld's integral representation of e^{ikR}/R ([7]; see also [2], page 414 and following)

$$\frac{e^{ikR}}{R} = \int_0^{\infty} J_0\{\tau[r^2 + \rho^2 - 2r\rho\cos(\varphi - \theta)]^{1/2}\} \times e^{-|x|(\tau^2-k^2)^{1/2}} \frac{\tau d\tau}{(\tau^2 - k^2)^{1/2}}$$

so that (33) becomes

$$I_n = \int_0^{2\pi} d\theta \int_0^{\infty} \frac{\tau d\tau}{(\tau^2 - k^2)^{1/2}} \times \int_{-\infty}^{\infty} J_0\{\tau[r^2 + \rho^2 - 2r\rho\cos(\varphi - \theta)]^{1/2}\} \times e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_n x} dx. \tag{34}$$

To reduce (34) further, we employ Graf's addition formula ([8], page 360)

$$e^{i\nu\psi} J_\nu(\omega) = \sum_{m=-\infty}^{\infty} J_{\nu+m}(Z) J_m(z) e^{im\varphi} \tag{35}$$

in which*

$$Z - z\cos\varphi = \omega\cos\psi, \quad z\sin\varphi = \omega\sin\psi$$
$$\omega = (Z^2 + z^2 - 2zZ\cos\varphi)^{1/2}$$

and ψ is rendered unique by the requirement that $\psi \to 0$ as $z \to 0$. When $\nu = 0$ in Graf's formula, the value of ψ is immaterial, so that, in (34)

$$J_0\{\tau[r^2 + \rho^2 - 2r\rho\cos(\varphi - \theta)]^{1/2}\} = \sum_{m=-\infty}^{\infty} J_m(\tau r) J_m(\tau\rho) e^{im(\varphi-\theta)}.$$

On substituting the last expression into (34) and again interchanging orders, we obtain

* Of course, the symbols ω, ν, ψ, z, and so on, in (35) have nothing to do with those in the expressions being studied.

$$I_n = \sum_{m=-\infty}^{\infty} e^{im\varphi} \times \int_0^{2\pi} e^{-im\theta} d\theta \int_0^{\infty} \frac{J_m(\tau r)\tau d\tau}{(\tau^2 - k^2)^{1/2}} \times \int_{-\infty}^{\infty} J_m(\tau\rho) e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_n x} dx$$
$$= 2\pi \int_0^{\infty} \frac{J_0(\tau r)\tau d\tau}{(\tau^2 - k^2)^{1/2}} \times \int_{-\infty}^{\infty} J_0\left\{\tau\left[a+B\sin\frac{2\pi}{L}(x+z)\right]\right\} \times e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_n x} dx. \quad (36)$$

To evaluate the integral with respect to x in (36), we must find the Fourier development of the function $J_0\left\{\tau\left[a + B\sin\frac{2\pi}{L}(x+z)\right]\right\}$, which may be done by two more applications of Graf's formula (35). If in the latter we put $\varphi = \pi$, then $\omega = Z + z$, so that for $\nu = 0$ (35) becomes

$$J_0(Z+z) = \sum_{m=-\infty}^{\infty} (-1)^m J_m(Z) J_m(z)$$

and therefore

$$J_0\left\{\tau\left[a + B\sin\frac{2\pi}{L}(x+z)\right]\right\} = \sum_{m=-\infty}^{\infty} (-1)^m J_m(\tau a) \times J_m\left[\tau B \sin\frac{2\pi}{L}(x+z)\right]. \quad (37)$$

If, on the other hand, one sets $Z = z$ in (35), we find $\psi = (\pi - \varphi)/2$, and

$$J_m\left(2Z\sin\frac{\varphi}{2}\right) = \sum_{s=-\infty}^{\infty} i^{-m} J_{m+s}(Z) J_s(Z) e^{is\varphi} e^{-im(\varphi/2)}$$

from which we have

$$J_m\left[\tau B\sin\frac{2\pi}{L}(x+z)\right] = \sum_{s=-\infty}^{\infty} i^{-m} J_{m+s}\left(\tau\frac{B}{2}\right) \times J_s\left(\tau\frac{B}{2}\right) e^{i(2\pi/L)(m+2s)(x+z)}$$

and therefore (37) becomes

$$J_0\left\{\tau\left[a + B\sin\frac{2\pi}{L}(x+z)\right]\right\} = \sum_m \sum_s (-1)^m i^{-m} J_m(\tau a) \times J_{m+s}\left(\tau\frac{B}{2}\right) J_s\left(\tau\frac{B}{2}\right) e^{i(2\pi/L)(m+2s)(x+z)}. \quad (38)$$

If, in (38), we make $m + 2s$ a new summation index, then

$$J_0\left\{\tau\left[a + B\sin\frac{2\pi}{L}(x+z)\right]\right\} = \sum_m \sum_s (-1)^s i^m J_s\left(\tau\frac{B}{2}\right) \times J_{m-s}\left(\tau\frac{B}{2}\right) J_{m-2s}(\tau a) e^{i(2\pi m/L)(x+z)}. \quad (39)$$

We now substitute (39) in (36) and get

$$I_n = 2\pi \sum_m \sum_s (-1)^s i^m e^{i(2\pi m/L)z} \times \int_0^{\infty} J_0(\tau r) J_s\left(\tau\frac{B}{2}\right) \times J_{m-s}\left(\tau\frac{B}{2}\right) J_{m-2s}(\tau a) \frac{\tau d\tau}{(\tau^2 - k^2)^{1/2}} \times \int_{-\infty}^{\infty} e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_{n+m} x} dx. \quad (40)$$

The first integral in (40) now gives

$$\int_{-\infty}^{\infty} \cdots = \frac{2(\tau^2 - k^2)^{1/2}}{\tau^2 + \gamma_{n+m}^2}$$

where $\gamma_{n+m}^2 = \beta_{n+m}^2 - k^2$. Then (40) becomes

$$I_n = 4\pi \sum_m \sum_s (-1)^s i^m e^{i(2\pi m/L)z} \times \int_0^{\infty} J_0(\tau r) J_s\left(\tau\frac{B}{2}\right) \times J_{m-s}\left(\tau\frac{B}{2}\right) J_{m-2s}(\tau a) \frac{\tau d\tau}{\tau^2 + \gamma_{n+m}^2}. \quad (41)$$

Thanks to a theorem of Watson ([8], page 430), the integral in (41) may be found exactly, and is given by

$$b_{ms} I_0(\gamma_{n+m} r) I_s\left(\gamma_{n+m}\frac{B}{2}\right) \times I_{m-s}\left(\gamma_{n+m}\frac{B}{2}\right) K_{m-2s}(\gamma_{n+m} a) \quad (42A)$$

provided $r < a - B$. In (42A), $I_n(x)$ and $K_n(x)$ are the modified Bessel and Hankel functions, respectively, and the coefficient b_{ms} represents a simple determination of sign. If we let

$$\begin{aligned} \epsilon_s &= 1, \qquad s \geqslant 0 \\ &= (-1)^s, \quad s < 0 \end{aligned}$$

then

$$\begin{aligned} b_{ms} &= -\epsilon_s \epsilon_{m-s} \epsilon_{m-2s} (-1)^{p/2} \\ p &= 2 + |s| + |m - s| - |m - 2s|. \qquad (42\text{B}) \end{aligned}$$

We thus have

$$\begin{aligned} I_n = 4\pi \sum_m \sum_s (-1)^s i^m b_{ms} \\ \times e^{i(2\pi m/L)z} I_0(\gamma_{n+m} r) I_s \left(\gamma_{n+m} \frac{B}{2}\right) \\ \times I_{m-s} \left(\gamma_{n+m} \frac{B}{2}\right) K_{m-2s}(\gamma_{n+m} a). \qquad (43) \end{aligned}$$

When we put (43) back in (31B), we obtain an expression of the form

$$\begin{aligned} (\text{constant}) \times \sum_n \sum_m \sum_s (-1)^s i^m b_{ms} B_n e^{i\beta_{n+m} z} \\ \times I_0(\gamma_{n+m} r) I_s \left(\gamma_{n+m} \frac{B}{2}\right) \\ \times I_{m-s} \left(\gamma_{n+m} \frac{B}{2}\right) K_{m-2s}(\gamma_{n+m} a). \qquad (44) \end{aligned}$$

To isolate more clearly the relative space-harmonic amplitudes in (44), we "change variables" in the summation indices, making $m + n$ a new index*: then (44) becomes

$$\begin{aligned} (\text{constant}) \\ \times \sum_{n=-\infty}^{\infty} F_n(\gamma_n B, \gamma_n a) I_0(\gamma_n r) e^{i\beta_n z} \qquad (45) \end{aligned}$$

where

$$\begin{aligned} F_n(\gamma_n B, \gamma_n a) = \sum_m \sum_s (-1)^s i^m b_{ms} B_{n-m} \\ \times I_s \left(\gamma_n \frac{B}{2}\right) I_{m-s} \left(\gamma_n \frac{B}{2}\right) K_{m-2s}(\gamma_n a). \qquad (46) \end{aligned}$$

* In (44) set $\nu = m + n$, keeping m fixed with $n = \nu - m$, and sum over ν, m, and s. Then replace ν by n.

Then we have for the potentials A_z and Φ of (31)

$$\begin{aligned} A_z = \frac{i\omega\mu\epsilon E_0 a}{\gamma} J_1(\gamma a) \\ \times \sum_n F_n(\gamma_n B, \gamma_n a) I_0(\gamma_n r) e^{i\beta_n z} \qquad (47\text{A}) \\ \Phi = \frac{i\beta E_0 a (1 + \sigma^2)^{1/2}}{\gamma} J_1(\gamma a) \\ \times \sum_n G_n(\gamma_n B, \gamma_n a) I_0(\gamma_n r) e^{i\beta_n z} \qquad (47\text{B}) \end{aligned}$$

where $G_n(\gamma_n B, \gamma_n a)$ in (47B) is given by (46) with B_{n-m} in the latter replaced by D_{n-m}.

The integration in (31A) differs from the preceding calculation only in certain details. In place of (33), we have

$$\bar{I}_n = \int_0^{2\pi} \cos(\theta - \varphi) d\theta \int_{-\infty}^{\infty} \frac{e^{ikR}}{R} e^{i\beta_n x} dx$$

which means that the first equation in (36) is replaced by

$$\begin{aligned} \bar{I}_n = \sum_{m=-\infty}^{\infty} e^{im\varphi} \int_0^{2\pi} e^{-im\theta} \cos(\theta - \varphi) d\theta \\ \times \int_0^{\infty} \frac{J_m(\tau r)\tau d\tau}{(\tau^2 - k^2)^{1/2}} \\ \times \int_{-\infty}^{\infty} J_m(\tau\rho) e^{-|x|(\tau^2-k^2)^{1/2}} e^{-\beta_n x} dx \\ = 2\pi \int_0^{2\pi} \frac{J_1(\tau r)\tau d\tau}{(\tau^2 - k^2)^{1/2}} \\ \times \int_{-\infty}^{\infty} J_1 \left\{ \tau \left[a + B \sin \frac{2\pi}{L} (x + z) \right] \right\} \\ \times e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_n x} dx \end{aligned}$$

and we must apply Graf's formula (35) with $\nu = 1$ and $\varphi = \pi$ in the latter, to get

$$\begin{aligned} J_1 \left\{ \tau \left[a + B \sin \frac{2\pi}{L} (x + z) \right] \right\} \\ = \sum_{m=-\infty}^{\infty} (-1)^m J_{m+1}(\tau a) \\ \times J_m \left[\tau B \sin \frac{2\pi}{L} (x + z) \right] \\ = \sum_m \sum_s (-1)^s i^m J_s \left(\tau \frac{B}{2}\right) \\ \times J_{m-s} \left(\tau \frac{B}{2}\right) J_{m-2s+1}(\tau a) e^{i(2\pi m/L)(x+z)} \end{aligned}$$

from (38). We have, then

$$\bar{I}_n = 2\pi \sum_m \sum_s (-1)^s i^m e^{i(2\pi m/L)z}$$
$$\times \int_0^\infty J_1(\tau r) J_s\left(\tau \frac{B}{2}\right)$$
$$\times J_{m-s}\left(\tau \frac{B}{2}\right) J_{m-2s+1}(\tau a) \frac{\tau d\tau}{(\tau^2 - k^2)^{1/2}}$$
$$\times \int_{-\infty}^{\infty} e^{-|x|(\tau^2-k^2)^{1/2}} e^{i\beta_{n+m}x} dx$$
$$= 4\pi \sum_m \sum_s (-1)^s i^m e^{i(2\pi m/L)z}$$
$$\times \int_0^\infty J_1(\tau r) J_s\left(\tau \frac{B}{2}\right)$$
$$\times J_{m-s}\left(\tau \frac{B}{2}\right) J_{m-2s+1}(\tau a) \frac{\tau d\tau}{\tau^2 + \gamma_{n+m}^2}. \quad (48)$$

The theorem of Watson already cited may be used to evaluate the integral in (48), which is

$$c_{ms} I_1(\gamma_{n+m} r) I_s\left(\gamma_{n+m} \frac{B}{2}\right)$$
$$\times I_{m-s}\left(\gamma_{n+m} \frac{B}{2}\right) K_{m-2s+1}(\gamma_{n+m} a)$$

where

$$c_{ms} = -\epsilon_s \epsilon_{m-s} \epsilon_{m-2s+1} (-1)^{q/2}$$
$$q = 3 + |s| + |m-s| - |m-2s+1| \quad (49)$$
$$(m, s = 0, \pm 1, \pm 2, \cdots).$$

Hence

$$\bar{I}_n = 4\pi \sum_m \sum_s (-1)^s i^m c_{ms} e^{i(2\pi m/L)z} I_1(\gamma_{n+m} r)$$
$$\times I_s\left(\gamma_{n+m} \frac{B}{2}\right) I_{m-s}\left(\gamma_{n+m} \frac{B}{2}\right) K_{m-2s+1}(\gamma_{n+m} a)$$

which, when substituted in (31A), gives an expression proportional to

$$\sum_n \sum_m \sum_s (-1)^s i^m c_{ms} E_n e^{i\beta_{n+m} z} I_1(\gamma_{n+m} r)$$
$$\times I_s\left(\gamma_{n+m} \frac{B}{2}\right)$$
$$\times I_{m-s}\left(\gamma_{n+m} \frac{B}{2}\right) K_{m-2s+1}(\gamma_{n+m} a). \quad (50)$$

Making the same change of summation index in (50) that was used in (44), and multiplying by the necessary constant, we have for A_r

$$A_r = \frac{i\omega\mu\epsilon E_0 \sigma a}{\gamma} J_1(\gamma a)$$
$$\times \sum_{n=-\infty}^{\infty} H_n(\gamma_n B, \gamma_n a) I_1(\gamma_n r) e^{i\beta_n z} \quad (51A)$$

along with the other potential components, which we rewrite here for convenience.

$$A_z = \frac{i\omega\mu\epsilon E_0 a}{\gamma} J_1(\gamma a)$$
$$\times \sum_n F_n(\gamma_n B, \gamma_n a) I_0(\gamma_n r) e^{i\beta_n z} \quad (51B)$$
$$\Phi = \frac{i\beta E_0 a (1 + \sigma^2)^{1/2}}{\gamma} J_1(\gamma a)$$
$$\times \sum_n G_n(\gamma_n B, \gamma_n a) I_0(\gamma_n r) e^{i\beta_n z} \quad (51C)$$

where, in (51A),

$$H_n(\gamma_n B, \gamma_n a)$$
$$= \sum_m \sum_s (-1)^s i^m c_{ms} E_{n-m}$$
$$\times I_s\left(\gamma_n \frac{B}{2}\right) I_{m-s}\left(\gamma_n \frac{B}{2}\right) K_{m-2s+1}(\gamma_n a). \quad (52)$$

From the potentials **A** and Φ given by (51), we may now obtain the field vectors themselves, from the formulas (16); the latter give, in this case

$$E_r = -\frac{\partial \Phi}{\partial r} + i\omega A_r \quad \mu H_r = 0$$
$$E_\varphi = 0 \quad \mu H_\varphi = \frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \quad (53)$$
$$E_z = -\frac{\partial \Phi}{\partial z} + i\omega A_z \quad \mu H_z = 0.$$

Applying (53) to the potentials (51), we have

$$E_r = -\frac{E_0 a J_1(\gamma a)}{\gamma}$$
$$\times \sum_{n=-\infty}^{\infty} [i\beta(1+\sigma^2)^{1/2} \gamma_n G_n(\gamma_n B, \gamma_n a)$$
$$+ k^2 \sigma H_n(\gamma_n B, \gamma_n a)] I_1(\gamma_n r) e^{i\beta_n z} \quad (54A)$$
$$E_z = \frac{E_0 a J_1(\gamma a)}{\gamma}$$
$$\times \sum_{n=-\infty}^{\infty} [\beta\beta_n (1+\sigma^2)^{1/2} G_n(\gamma_n B, \gamma_n a)$$
$$- k^2 F_n(\gamma_n B, \gamma_n a)] I_0(\gamma_n r) e^{i\beta_n z} \quad (54B)$$

$$H_\varphi = \frac{i\omega\epsilon E_0 a J_1(\gamma a)}{\gamma} \times \sum_{n=-\infty}^{\infty} [i\beta_n\sigma H_n(\gamma_n B, \gamma_n a) - \gamma_n F_n(\gamma_n B, \gamma_n a)] I_1(\gamma_n r) e^{i\beta_n z} \quad (54C)$$

for $r < a - b$.

Having obtained (54), the heaviest part of our analysis is concluded. To summarize, we remark that expressions (54) are the components of field vectors **E** and **H** of the wave propagating in the periodic guide with wall surface Σ, corresponding to the approximate surface current and charge densities given by equations (18) and (19). With the latter, integrals (20) representing the vector and scalar potentials **A** and Φ were obtained. It was found that these integrals could be evaluated without making any further approximations, that is, the geometry of the guide is taken into account exactly. (Because of the latter circumstance, it is possible to show that expressions (54) represent the correct angularly independent fields in such a guide, due to the fact that the correct densities do not differ *in form* from those assumed.)

In the derivation of (54), it was necessary to represent several periodic functions by their Fourier developments (for example, in (22)–(29)). This was generally done without explicit evaluation of the corresponding Fourier coefficients. Rather than burden the text with such computations, we give these coefficients, together with relevant formulas for their detailed calculation, in Table 1.

It is also necessary to point out that our calculations have been *formal*, in the sense that frequent interchange of orders of summation and integration have been made without any comment. Here, it must suffice to state that by making proper use of asymptotic formulas for the modified Bessel functions, the series expressions (54) may be shown to be uniformly convergent in the domain $0 \leqslant r < a - B$. They thus represent solutions of Maxwell's equations there.

4. Some Properties of Fields in Axially Corrugated Guide

We turn now to the interpretation of (54) and the derivation therefrom of some practically useful expressions, from the standpoint of applying such a guide as the slow-wave structure of a traveling-wave tube. We thus envisage a cylindrical electron beam coaxial with the guide, as shown in Figure 2. (Our further application of (54) will, of course, be only approximate because of the fact that we are obliged to approximate to the phase-shift factor β_0 by an expression proportional to the phase-shift factor β for straight guide.)

Let us notice first that the formulas (54) have the same general form as the field expressions for all slow-wave structures possessing a cylindrical beam region (here, $r < a - B$), for example, the disc-loaded circular waveguide (Brillouin [9], Slater [13], Chu and Hansen [10]), both single and cross-wound helices (Sensiper [11], Chodorow and Chu [12]), and various ring-and-bar lines (Birdsall and Everhart [14]). In common with solutions for the last-named structures, the solutions (54) express the field as the superposition of infinitely many partial waves, or space-harmonic waves, the n-th one of which has the phase-shift factor β_n. Thus, rewriting (54B) slightly

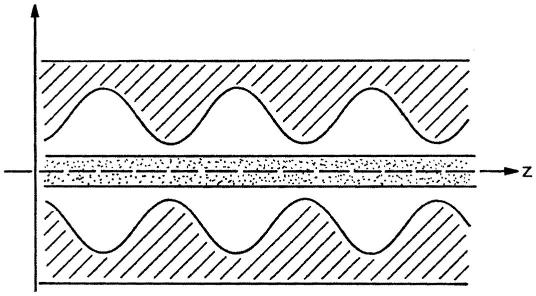

Figure 2—Longitudinal section of a traveling-wave tube having a solid electron beam, employing axially corrugated circular guide for its slow-wave structure.

$$
\begin{aligned}
E_z &= \sum_n E_z^{(n)}(r)e^{i\beta_n z} \\
&= \cdots + E_z^{(-1)}(r)e^{i\beta_{-1}z} \\
&\quad + E_z^{(0)}(r)e^{i\beta_0 z} + E_z^{(1)}(r)e^{i\beta_1 z} + \cdots \qquad (55)
\end{aligned}
$$

In addition, (54) reveals the existence and location for axially corrugated guide of the stop and pass bands in the phase–frequency plane (see Slater [3], chapter 8). The space-harmonic components of (54) are all propagating waves provided $\gamma_n^2 > 0$ for every n ($n = 0, \pm 1, \pm 2, \cdots$). Since

$$
\begin{aligned}
\gamma_n^2 &= \beta_n^2 - k^2 \\
&= \left(\beta_0 + \frac{2\pi n}{L} - k\right)\left(\beta_0 + \frac{2\pi n}{L} + k\right)
\end{aligned}
$$

we therefore require that both factors on the right have the same sign for every such n. In dimensionless form

$$(\beta_0 L - kL + 2\pi n)(\beta_0 L + kL + 2\pi n) > 0. \qquad (56)$$

Let n be fixed, but arbitrary, and consider the lines $\beta_0 L \pm kL + 2\pi n = 0$ in the $\beta_0 L$, kL plane. Then one sees that both factors on the left in (56) have the same sign if, and only if, the point $(\beta_0 L, kL)$ lies in either of the unshaded regions of Figure 3. Letting n take on every integer value, we obtain the *Brillouin diagram* [9] of Figure 4 (in which we have omitted the physically unimportant region $kL < 0$). We see that the entire region $kL \geqslant \pi$ is excluded, which merely means that

TABLE 1

Table of Fourier Coefficients and Associated Data for Periodic Functions Appearing in the Analysis of Periodically Deformed Waveguides. (Index $n = 0, \pm 1, \pm 2, \cdots$, Unless Otherwise Stated.)

Coefficient and Formula	Remarks
$A_n = J_n(\Gamma L)$	$\Gamma = \dfrac{\beta a_1}{4\pi}(1 + \sigma^2)^{1/2}$ $a_1 = \dfrac{4}{3\pi l^2}[(2 - l^2)E(l) + 2(l^2 - 1)K(l)]$ $K(l)[E(l)]$ = elliptic integral of first (second) kind
$B_n = A_n + \dfrac{iB}{2a}(A_{n+1} - A_{n-1})$	$B_0 = J_0(\Gamma L)$; $B_{\pm 1} = \dfrac{iB}{2a}[J_1(\Gamma L) \mp J_0(\Gamma L)]$; and so on
$C_n = 0$, n odd $= \dfrac{2}{\pi}\displaystyle\int_0^{\pi/2}(1 - l^2 \sin^2 x)^{1/2} \cos nx\, dx$, n even	$C_0 = \dfrac{2}{\pi}E(l)$; $C_1 = a_1/2$
$D_n = \displaystyle\sum_{p=-\infty}^{\infty} B_p C_{n-p}$	
$E_n = \frac{1}{2}(B_{n+1} + B_{n-1})$	
$M_n = \dfrac{8}{\pi}\displaystyle\int_0^{\pi/2} \frac{\cos x \cos nx\, dx}{(1 - l^2 \sin^2 x)^{1/2}}$ ($n = 1, 3, 5, \cdots$)	$M_1 = \dfrac{8}{\pi l^2}[(l^2 - 1)K(l) + E(l)]$ $M_3 = \dfrac{8}{3\pi l^4}[(3l^4 - 11l^2 + 8)K(l) + (7l^2 - 8)E(l)]$
$N_n = \displaystyle\sum_{m=-\infty}^{\infty} M_{2m+1} J_{n-m}(\Gamma L)$	See also (80) and (82)
$P_{2n} = \dfrac{4}{\pi}\displaystyle\int_0^{\pi/2} \frac{\cos 2nx\, dx}{(1 - l^2 \sin^2 x)^{1/2}}$ ($n = 1, 2, 3, \cdots$)	$P_0 = \dfrac{2}{\pi}K(l)$ $P_2 = \dfrac{4}{\pi l^2}[(l^2 - 2)K(l) + 2E(l)]$
$Q_n = \displaystyle\sum_{m=-\infty}^{\infty} (-1)^m J_{2m}(\Gamma_1) J_{n-m}(\Gamma L)$	See also (84)

we must have $L < \lambda/2$, as expected. It follows that propagation is possible only for those values of the frequency (kL) and phase ($\beta_0 L$) which lie in one of the unshaded triangular regions of Figure 4, that is, in a pass band of the guide. A different graphical representation of these pass bands is obtained when we consider the phase velocities of the various component waves, which we discuss next.

The quantities of most importance, from our standpoint, are (a) the relative phase velocities of the lowest-order space-harmonic waves, that is, those with phase-shift factors β_{-1}, β_0, β_1, and (b) the beam coupling impedance of each such wave, given by (in the notation of (55))

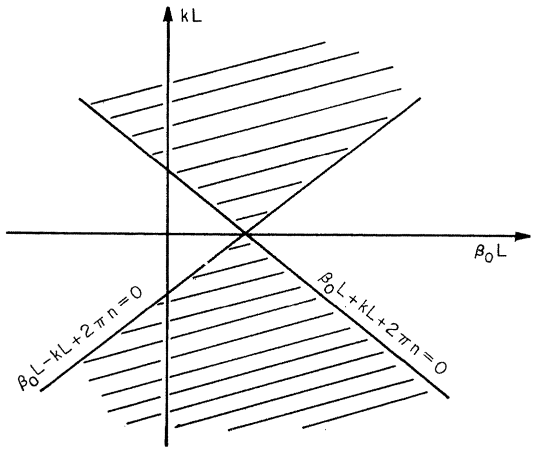

Figure 3—Showing the region in which $\gamma_n^2 = \beta_n^2 - k^2$ is positive for a fixed but arbitrary value of n, in the $\beta_0 L$, kL plane. For each integer n, $\gamma_n^2 > 0$ only in the cones opening to the right and left of the vertex $(-2\pi n, 0)$.

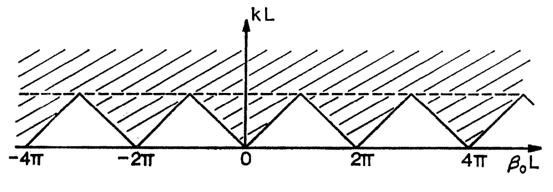

Figure 4—Stop and pass bands (unshaded regions) in the phase–frequency plane for axially corrugated circular guide.

$$Z_n = \frac{\overline{|E_z^{(n)}(r)|^2}}{2\beta_n^2 P}, \quad n = 0, \pm 1, \pm 2, \cdots \qquad (57)$$

in which the numerator is the average value of the relative amplitude squared, $|E_z^{(n)}(r)|^2$,

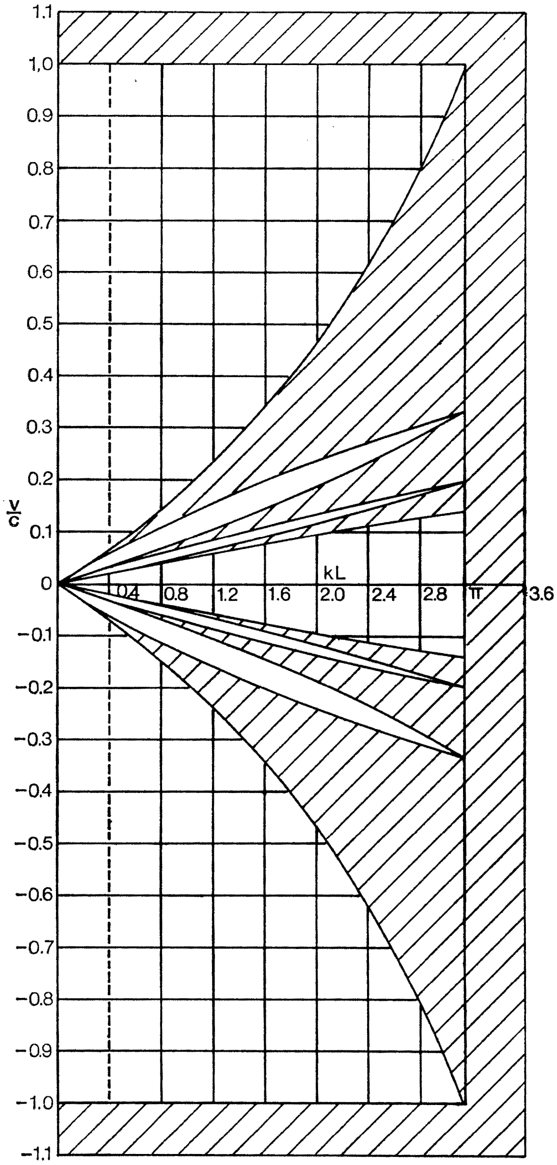

Figure 5—The character of the stop and pass bands (unshaded regions) in the plane of relative phase velocity versus frequency. In this figure, the first three pass bands are shown. The vertical dashed line on the left represents the low-frequency cutoff value of kL.

where the average is taken over the beam cross section, and P is the total power carried by the entire field (54) (see Beck [15], page 54 and following; and Doehler [16]).

Considering the quantities (a), the relative phase velocity v_n/c of the wave with phase constant β_n is given by

$$\frac{v_n}{c} = \frac{k}{\beta_n} = \frac{kL}{\beta_n L} = \frac{kL}{\frac{2}{\pi} E(l)(1+\sigma^2)^{1/2}\beta L + 2\pi n} \quad (58)$$

$$(n = 0, \pm 1, \pm 2, \cdots)$$

from (21), where β is the phase-shift factor for straight guide of radius a. (The quantity $(2/\pi)E(l)(1+\sigma^2)^{1/2}$ is thus the velocity reduction factor due to the deformation of the guide wall, for the $n = 0$ wave.) We recall that β is given by (17B), namely, $\beta = [k^2 - (x_0/a)^2]^{1/2}$. The value $k = x_0/a$ for which $\beta = 0$ determines the cutoff frequency for the unperturbed TM_{10} mode. In view of the geometry of axially corrugated guide, we re-estimate the cutoff frequency and use

$$\beta = \left[k^2 - \left(\frac{x_0}{a - B}\right)^2\right]^{1/2}.$$

Then (58) becomes

$$\frac{v_n}{c} = \frac{kL}{\frac{2}{\pi} E(l)(1+\sigma^2)^{1/2}\left[(kL)^2 - x_0^2\left(\frac{L}{a - B}\right)^2\right]^{1/2} + 2\pi n}. \quad (59)$$

Before considering (59), we point out that the pass and stop bands possess a simple graphical representation in the phase velocity versus frequency plane, as well as that shown in Figure 4. The boundary lines of these regions in the plane of Figure 4 are given by $\beta_0 L = \pm kL - 2\pi n$. Hence the corresponding boundary curves in the velocity versus frequency plane are given by

$$\frac{v}{c} = \frac{kL}{\pm kL - 2\pi n} \; (n = 0, \pm 1, \pm 2, \cdots). \quad (60)$$

The pass bands of the propagation are now the *unshaded* regions of Figure 5, in which we have sketched some of the boundary curves (60). It is seen that the diagram is symmetric about the kL axis, so that only the upper half is needed in any particular graphical representation of the phase velocity. In addition, for any given choice of guide dimensions, there will be a particular value of $kL = (kL)_c$ $= x_0[L/(a - B)]$ in our approximation) below which propagation is also cut off, indicated by the vertical dashed line in Figure 5.

Turning now to (59) itself, it is apparent that for each value of n and $kL/(kL)_c$, the relative phase velocity is determined by specifying the ratios B/L and $L/(a - B)$. Having chosen a set of values for these ratios, a "universal" family of relative phase velocity curves may be constructed. We have not done this here, however, but give instead in Figure 6 a few curves of the phase velocity for some specific values of the structure dimensions, which adequately show the effects of varying these dimensions through a reasonable range. Figure 6 also shows the location of the stop bands already discussed and contains graphs of the velocities for the three lowest-order harmonics. Some of these graphs are terminated discontinuously at the edge of the pass band. This merely means that for frequencies near the edge of a pass band, our approximation to the phase is a poor one. But in the application contemplated here, one would not operate in such a zone of frequencies. In particular, Figure 6 shows that for a given mean radius a, values of B and the period L exist for which the relative velocity v_0/c is small, and that a large range of frequencies exists within which v_0/c is substantially constant over the range.

Turning next to the beam interaction impedance (57), we are obliged to deal directly with expression (54B) for E_z itself. To calculate $|E_z|$ from the latter, we must evaluate the coefficients $F_n(\gamma_n B, \gamma_n a)$ and $G_n(\gamma_n B, \gamma_n a)$ (where we recall that G_n is obtained from F_n by replacing B_n in the latter by D_n (Table 1)). A tedious but straightforward calculation gives the somewhat cumbersome expression

$$F_n(\gamma_n B, \gamma_n a) = B_n I_0^2\left(\gamma_n \frac{B}{2}\right) K_0(\gamma_n a)$$

$$+ 2\sum_{m=1}^{\infty}\left\{B_n I_m^2\left(\gamma_n \frac{B}{2}\right) K_{2m}(\gamma_n a) + \frac{i^m}{2}[B_{n-m} + (-1)^m B_{n+m}] I_0\left(\gamma_n \frac{B}{2}\right) I_m\left(\gamma_n \frac{B}{2}\right) K_m(\gamma_n a)\right.$$

$$\left. + i^m \sum_{s=1}^{\infty} (-1)^s I_s\left(\gamma_n \frac{B}{2}\right)[B_{n-m} Y_{ms}(\gamma_n B, \gamma_n a) + (-1)^m B_{n+m} Z_{ms}(\gamma_n B, \gamma_n a)]\right\}$$

$$(n = 0, \pm 1, \pm 2, \cdots)$$

in which

$$Y_{ms} = b_{ms} I_{m-s}\left(\gamma_n \frac{B}{2}\right) K_{m-2s}(\gamma_n a) + b_{m,-s} I_{m+s}\left(\gamma_n \frac{B}{2}\right) K_{m+2s}(\gamma_n a)$$

$$Z_{ms} = b_{-m,-s} I_{m-s}\left(\gamma_n \frac{B}{2}\right) K_{m-2s}(\gamma_n a) + b_{-m,s} I_{m+s}\left(\gamma_n \frac{B}{2}\right) K_{m+2s}(\gamma_n a)$$

and $b_{ms} = \pm 1$, according to (42A). These expressions show that accurate and detailed calculation of the impedance requires a computing facility of at least modest capacity. However, in the course of the preceding analysis, we did obtain the rather crude approximation

$$Z_0 = \left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{|\beta\beta_0(1+\sigma^2)^{1/2} - k^2|^2}{\pi k \beta \beta_0^2} K_0^2[\gamma_0(a-B)] \quad (61)$$

for beams of vanishingly small radius. We conjecture that (61) underestimates the actual impedance.

5. Propagation in a Periodically Bent Rectangular Guide

We now consider propagation in a perfectly conducting periodically deformed guide of rectangular cross section, a sketch of which is shown in Figure 7, and a longitudinal section in Figure 8. (Henceforth, we refer to it by the short phrase "bent guide.")

Bent guide, regarded as a slow-wave circuit for traveling-wave devices, was first considered by Kleinwächter [18], and—independently—by Wilmarth [19]. The first detailed analysis of such a circuit was given by the writer [20]. A somewhat more crude analysis by Cullen [21] appeared at about the same time. A specific application of bent guide to millimeter-wave amplification was considered by Snyder and Wilmarth [22]. Several detailed calculations of tube performance, based on the writer's earlier analysis [20], have been given in unpublished work by Asam and Grant [23]. In the author's initial study [20], only propagation of the perturbed TE_{10} mode was considered. In this paper, we consider propagation of the perturbed TM_{11} mode, as well. It will thus be seen that our method is, in fact, applicable to any mode in rectangular guide.

Although we present below the basic formulas needed to produce design criteria for amplifiers using bent guide, we have not given any detailed numerical results. Not only would such a discussion make our presentation unduly prolix, but, to be really useful, would have to include methods of making optimal choices for the relative structure dimensions. Therefore, such an analysis properly belongs in another paper which would take these results as the starting point.

Because of the more complicated geometry of bent guide, we are unable to establish a theory of propagation which is simultaneously rigorous and productive of useful expressions. On the other hand, the necessity of thus making additional simplifying assumptions leads to correspondingly simpler expressions, and furnishes a more detailed, albeit less accurate, description of the propagation.

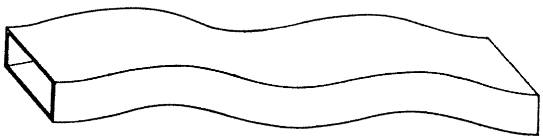

Figure 7—Sketch of periodically bent rectangular waveguide.

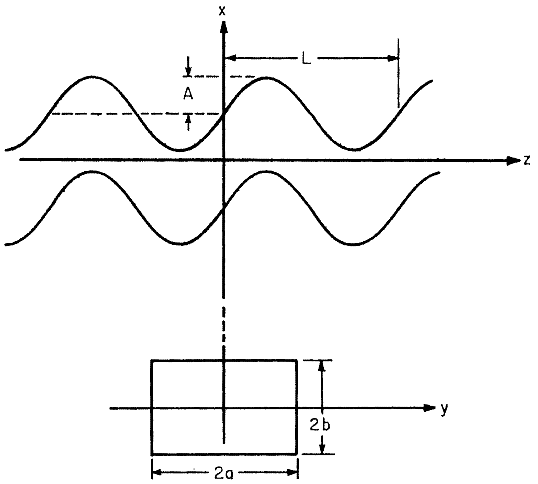

Figure 8—Longitudinal and cross sections of bent guide, showing the period L and amplitude of bending A. The dimensions of a cross section are 2a and 2b.

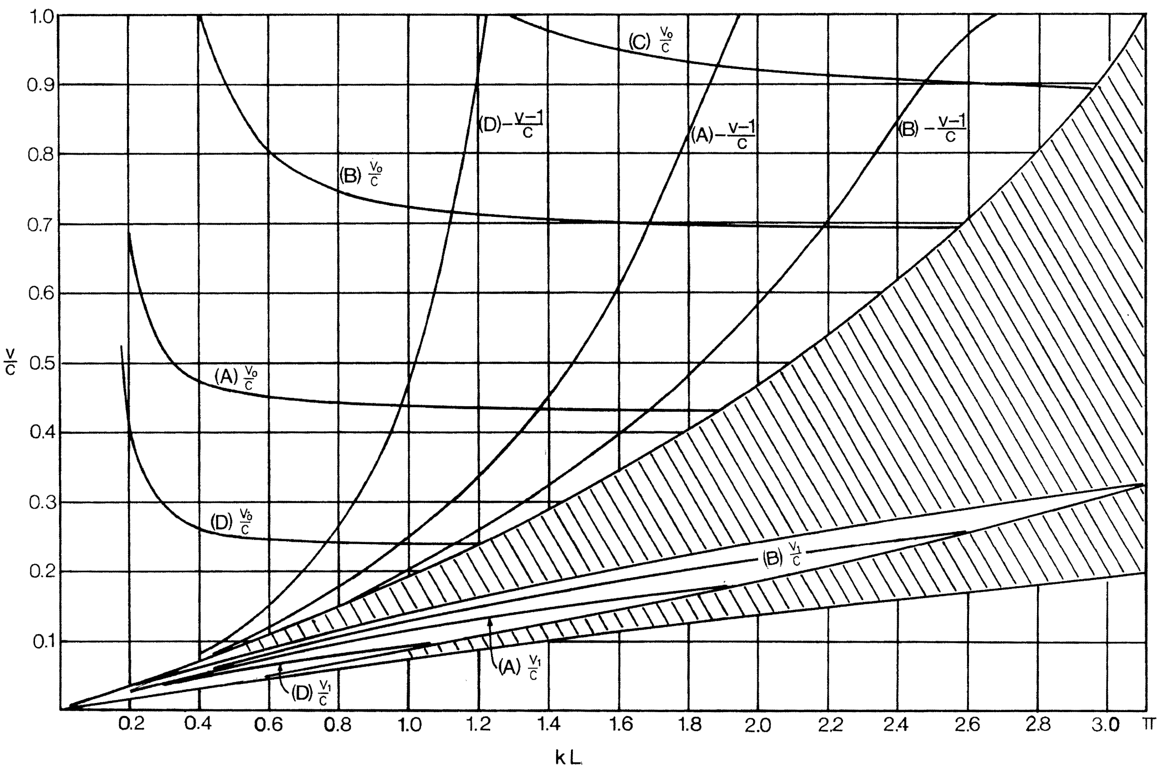

Figure 6—Relative phase velocities v_0/c, v_1/c, v_{-1}/c in axially corrugated guide for four different sets of structure dimensions. The dimensions (in any units) are (A) $a = 2$, $B = 0.0625$, $L = 0.125$; (B) $a = 2$, $B = 0.0625$, $L = 0.25$; (C) $a = 2$, $B = 0.0625$, $L = 0.5$; (D) $a = 2$, $B = 0.125$, $L = 0.125$.

We deal first with the geometry of the guide. (It will be found that several of the resulting expressions closely resemble those for axially corrugated guide.) Let the bounding walls of bent guide be disposed relative to rectangular coordinates as shown in Figures 8 and 9. We suppose that the upper and lower walls of bent guide are portions of surfaces belonging to the family of parallel undulating surfaces given by

$$\mathbf{X} = \left(\xi + A \sin \frac{2\pi}{L}\zeta, \eta, \zeta\right)$$

and that the upper and lower walls themselves are thus given by $\xi = \pm b (b > 0)$:

$$\mathbf{X} = \left(\pm b + A \sin \frac{2\pi}{L}\zeta, \eta, \zeta\right).$$

Then

$$\mathbf{X}_\eta = (0, 1, 0), \quad \mathbf{X}_\zeta = \left(\sigma \cos \frac{2\pi}{L}\zeta, 0, 1\right)$$

where $\sigma = 2\pi A/L$ and the corresponding unit vectors, tangent to the family and orthogonal to each other, are*

$$\mathbf{i}_\eta = (0, 1, 0)$$

$$\mathbf{i}_\zeta = \frac{\left(\sigma \cos \frac{2\pi}{L}\zeta, 0, 1\right)}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L}\zeta\right)^{1/2}}. \qquad (62)$$

* $\sigma = 2\pi A/L$ for bent guide and $= 2\pi B/L$ for axially corrugated guide.

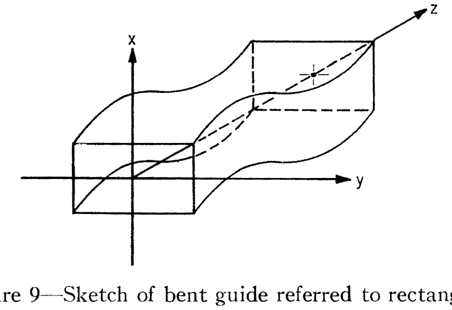

Figure 9—Sketch of bent guide referred to rectangular coordinates x, y, z. Parametric equations of the upper and lower faces are $x = \pm b + A \sin (2\pi/L)\zeta$, $y = \eta$, $z = \zeta$.

The unit normal $\mathbf{n}$ to any member of the family is given by

$$\mathbf{n} = \mathbf{i}_\eta \times \mathbf{i}_\zeta = \frac{\left(1, 0, -\sigma \cos \frac{2\pi}{L}\zeta\right)}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L}\zeta\right)^{1/2}}. \qquad (63)$$

The vectors $\mathbf{n}$, $\mathbf{i}_\eta$, $\mathbf{i}_\zeta$ thus correspond to $\mathbf{i}_x$, $\mathbf{i}_y$, $\mathbf{i}_z$ at any point in the interior of straight guide.

We now consider the field vectors themselves. The modes for straight rectangular guide are

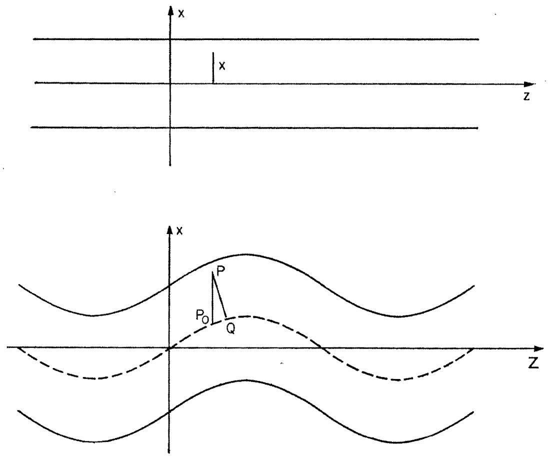

Figure 10—Comparison of the directed distances x and PQ in straight and bent guide, respectively. $PQ = (\mathbf{X} - \mathbf{X}_0)\cdot\mathbf{n}$, approximately; see equations (67) of the text.

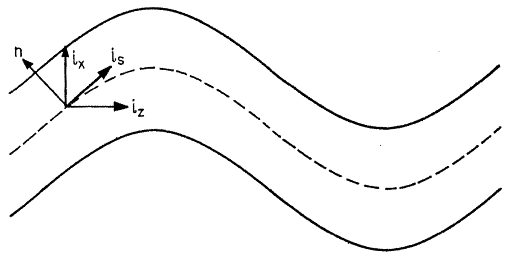

Figure 11—Comparing the unit vectors $\mathbf{n}$ and $\mathbf{i}_\zeta$ with the ordinary unit vectors $\mathbf{i}_x$ and $\mathbf{i}_z$ in rectangular coordinates at a typical interior point P of bent guide. The vector $\mathbf{i}_\eta = \mathbf{i}_y$ (not shown) is perpendicular to the plane of the sketch.

given by well-known expressions ([2], [24]). When they are referred to the rectangular coordinates appropriate to our analysis—placing the origin at the center of a cross-section—the electric field of the lowest-order H wave (TE_{10} mode) has the single component

$$E_x = -\frac{i\omega\mu}{\gamma^2}\frac{\pi H_0}{2a}\sin\frac{\pi}{2a}(y+a)e^{i\beta z} \quad (64)$$

while for the lowest-order E wave (TM_{11} mode)

$$\left.\begin{aligned} E_x &= \frac{i\beta}{\gamma^2}\frac{\pi E_0}{2b}\cos\frac{\pi}{2b}(x+b)\sin\frac{\pi}{2a}(y+a) \\ E_y &= \frac{i\beta}{\gamma^2}\frac{\pi E_0}{2a}\sin\frac{\pi}{2b}(x+b)\cos\frac{\pi}{2a}(y+a) \\ E_z &= E_0\sin\frac{\pi}{2b}(x+b)\sin\frac{\pi}{2a}(y+a) \end{aligned}\right\}\times e^{i\beta z} \quad (65)$$

where H_0 and E_0 are arbitrary constants, $\gamma^2 = k^2 - \beta^2$, and

$$\beta^2 = k^2 - \left(\frac{\pi}{2a}\right)^2 \text{ in (64)} \qquad = k^2 - \left(\frac{\pi}{2a}\right)^2 - \left(\frac{\pi}{2b}\right)^2 \text{ in (65).}$$

Then, for bent guide, we assume that *the amplitude A and period L of bending are of such smoothness that the fields propagate in bent guide unchanged in structure.* Thus $\mathbf{E} = \mathbf{i}_x E_x$ for the TE_{10} mode becomes $\mathbf{E} = \mathbf{n}E_n$, with (64) replaced by

$$E_n = -\frac{i\omega\mu}{\gamma^2}\frac{\pi H_0}{2a}\sin\frac{\pi}{2a}(\eta+a)e^{i\beta s(\zeta)} \quad (66)$$

where $s(\zeta)$ measures distance along the "axis" of bent guide. The components of the new TM_{11} mode are obtained similarly, with the slight added complication that at an arbitrary point P, the coordinate x must be replaced by the corresponding directed distance PQ in Figure 10. Letting $\mathbf{X}_0 = \left(A\sin\frac{2\pi}{L}\zeta, 0, \zeta\right)$ be the vector to P_0, we have, approximately,

$$PQ = (\mathbf{X} - \mathbf{X}_0)\cdot\mathbf{n} = \frac{\xi}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}}.$$

Then, in place of (65), we have the new components along $\mathbf{n}$, $\mathbf{i}_\eta$, $\mathbf{i}_\xi$:

$$\left.\begin{aligned} E_n &= \frac{i\beta}{\gamma^2}\frac{\pi E_0}{2b}\cos\frac{\pi}{2b}\left(\frac{\xi}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}}+b\right)\sin\frac{\pi}{2a}(\eta+a) \\ E_\eta &= \frac{i\beta}{\gamma^2}\frac{\pi E_0}{2a}\sin\frac{\pi}{2b}\left(\frac{\xi}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}}+b\right)\cos\frac{\pi}{2a}(\eta+a) \\ E_\zeta &= E_0\sin\frac{\pi}{2b}\left(\frac{\xi}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}\zeta\right)^{1/2}}+b\right)\sin\frac{\pi}{2a}(\eta+a) \end{aligned}\right\}\times e^{i\beta s(\zeta)}. \quad (67)$$

For analysis of the slow-wave properties of bent guide, however, we require the new fields just obtained but referred to the unit vectors in rectangular coordinates (Figure 11) and with components also expressed in rectangular coordinates. Expressed in terms of $\mathbf{i}_x$, $\mathbf{i}_y$, $\mathbf{i}_z$, we have from

(62) and (63)

$$\mathbf{n} = \frac{\mathbf{i}_x - \mathbf{i}_z \sigma \cos \frac{2\pi}{L} \zeta}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} \zeta\right)^{1/2}}, \quad \mathbf{i}_\eta = \mathbf{i}_y,$$

$$\mathbf{i}_\zeta = \frac{\mathbf{i}_x \sigma \cos \frac{2\pi}{L} \zeta + \mathbf{i}_z}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} \zeta\right)^{1/2}}. \quad (68)$$

Expressions (68) thus show that the new TE_{10} electric field, $\mathbf{n}E_n$, has a z component, and that $\mathbf{n}E_n + \mathbf{i}_\zeta E_\zeta$ is the part of the new TM_{11} field having a z component.

Let us first consider the simpler case (66). We have (replacing ζ by z, between which we no longer need distinguish)

$$\mathbf{E} = \mathbf{n}E_n = \frac{-\left(\mathbf{i}_x - \mathbf{i}_z \sigma \cos \frac{2\pi}{L} z\right)}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \times \frac{i\omega\mu}{\gamma^2} \frac{\pi H_0}{2a} \sin \frac{\pi}{2a} (y + a) e^{i\beta s(z)}$$

$$= -\mathbf{i}_x \frac{i\omega\mu}{\gamma^2} \frac{\pi H_0}{2a} \frac{\sin \frac{\pi}{2a} (y + a)}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} e^{i\beta s(z)} + \mathbf{i}_z \frac{i\omega\mu}{\gamma^2} \frac{\pi H_0}{2a} \frac{\sigma \cos \frac{2\pi}{L} z}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \times \sin \frac{\pi}{2a} (y + a) e^{i\beta s(z)}$$

so that the bending of the guide results in a z component of electric field given by

$$E_z = \frac{i\omega\mu}{\gamma^2} \frac{\pi H_0 \sigma}{2a} \sin \frac{\pi}{2a} (y + a) \times \frac{\cos \frac{2\pi}{L} z}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} e^{i\beta s(z)}. \quad (69)$$

Determination of the space-harmonic components of E_z now reduces to making proper Fourier developments of the last two terms on the right in (69). In the same way, expressions (67) and (68) yield

$$\mathbf{n}E_n + \mathbf{i}_\zeta E_\zeta = \left[\frac{\mathbf{i}_x - \mathbf{i}_z \cdot \cos \frac{2\pi}{L} z}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \frac{i\beta}{\gamma^2} \frac{\pi E_0}{2b} \cos \frac{\pi}{2b} \left(\frac{\xi}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} + b \right) \sin \frac{\pi}{2a} (\eta + a) \right.$$
$$\left. + \frac{\mathbf{i}_x \sigma \cos \frac{2\pi}{L} z + \mathbf{i}_z}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} E_0 \sin \frac{\pi}{2b} \left(\frac{\xi}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} + b \right) \sin \frac{\pi}{2a} (\eta + a) \right] e^{i\beta s(z)} \quad (70)$$

and (70) has the z component

$$E_0 \frac{\sin \frac{\pi}{2a} (\eta + a)}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \left[\sin \frac{\pi}{2b} \left(b + \frac{\xi}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \right) - \frac{i\beta\sigma\pi}{2b\gamma^2} \cos \frac{2\pi}{L} z \cos \frac{\pi}{2b} \left(b + \frac{\xi}{\left(1 + \sigma^2 \cos^2 \frac{2\pi}{L} z\right)^{1/2}} \right) \right] e^{i\beta s(z)}$$

which becomes, on setting $\eta = y$ and $\xi = x - A\cos\frac{2\pi}{L}z$

$$E_z = E_0 \sin\frac{\pi}{2a}(y+a)\left[\sin\frac{\pi}{2b}\left[b + \frac{x - A\cos\frac{2\pi}{L}z}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}}\right]\right.$$

$$\left. - \frac{i\beta\sigma\pi}{2b\gamma^2}\cos\frac{2\pi}{L}z\cos\frac{\pi}{2b}\left[b + \frac{x - A\cos\frac{2\pi}{L}z}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}}\right]\right]\frac{e^{i\beta s(z)}}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}}. \quad (71)$$

Expression (71) represents the z component of the TM_{11} electric field in bent guide, but referred to rectangular instead of the curvilinear coordinates ξ, η, ζ. Now

$$\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2} = (1+\sigma^2)^{1/2}\left(1 - l^2\sin^2\frac{2\pi}{L}z\right)^{1/2},$$

$$l = \frac{\sigma}{(1+\sigma^2)^{1/2}}$$

and in the argument

$$b + \frac{x - A\cos\frac{2\pi}{L}z}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}} \quad (72)$$

appearing in (71), we shall further assume that only terms of at most of the first order in l need be retained. But

$$\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{-1/2} \simeq \frac{1}{(1+\sigma^2)^{1/2}}\left(1 + \frac{l^2}{2}\sin^2\frac{2\pi}{L}z\right)$$

so that (72) is replaced by

$$b + \frac{1}{(1+\sigma^2)^{1/2}}\left(x - A\cos\frac{2\pi}{L}z\right). \quad (73)$$

Moreover, in expanding the sine and cosine of the simplified argument (73), the term $\sin\left(\frac{\pi A}{2b(1+\sigma^2)^{1/2}}\cos\frac{2\pi}{L}z\right)$ is of higher order in the (generally small) ratio $A/2b$ than the cosine of the same quantity. Hence, we replace the sine and cosine of (73) by

$$\begin{matrix}\sin\\ \cos\end{matrix}\frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{1/2}}\right) \times \cos\left(\frac{\pi A}{2b(1+\sigma^2)^{1/2}}\cos\frac{2\pi}{L}z\right)$$

respectively, whereupon we have in place of (71) the more manageable expression

$$E_z = E_0\left[\sin\frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{1/2}}\right) - \frac{i\beta\sigma\pi}{2b\gamma^2}\cos\frac{2\pi}{L}z\cos\frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{1/2}}\right)\right]$$

$$\times \sin\frac{\pi}{2a}(y+a)\frac{\cos\left(\frac{\pi A}{2b(1+\sigma^2)^{1/2}}\cos\frac{2\pi}{L}z\right)}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}}e^{i\beta s(z)}. \quad (74)$$

We must now obtain the space-harmonic developments of (69) and (74). Let us first consider the simpler expression (69). We write

$$\frac{\cos\frac{2\pi}{L}z}{\left(1+\sigma^2\cos^2\frac{2\pi}{L}z\right)^{1/2}} = \frac{1}{(1+\sigma^2)^{1/2}}\frac{\cos\frac{2\pi}{L}z}{\left(1 - l^2\sin^2\frac{2\pi}{L}z\right)^{1/2}}$$

and we have

$$\frac{\cos\frac{2\pi}{L}z}{\left(1-l^2\sin^2\frac{2\pi}{L}z\right)^{1/2}} = \sum_{n=0}^{\infty} M_{2n+1}\cos\frac{2\pi(2n+1)}{L}z = \tfrac{1}{2}\sum_{n=-\infty}^{\infty} M_{2n+1}e^{i(2\pi/L)(2n+1)z} \qquad (75)$$

provided we set $M_{-n} = M_n$. (Calculation shows that only the Fourier coefficients of odd index fail to vanish. Expressions for the various Fourier coefficients which occur in the analysis of bent guide are given in Table 1.)

The phase factor $\exp[i\beta s(z)]$ appearing in both (69) and (74) is formally the same as that for axially corrugated guide already considered above, provided merely that one replaces B by A in the latter. Its periodic part thus has the same Fourier development, and we again have

$$e^{i\beta s(z)} = e^{i\beta_0 z}\sum_{n=-\infty}^{\infty} J_n(\Gamma L)e^{i(4n\pi/L)z} \qquad (76)$$

where

$$\beta_0 = \frac{2}{\pi}E(l)(1+\sigma^2)^{1/2}\beta \qquad (77)$$

in which $\beta = [k^2-(\pi/2a)^2]^{1/2}$ is just the phase-shift factor in straight rectangular guide, and where Γ is a constant depending on β and the dimensions of the guide; the formula for Γ is given in Table I. (Since both bent guide and axially corrugated guide have the same arc-length function, Γ and the velocity reduction factor are the same in each case.) Combining expressions (75) and (76), (69) becomes

$$E_z = \frac{i\omega\mu\pi H_0\sigma}{4a\gamma^2(1+\sigma^2)^{1/2}}\sin\frac{\pi}{2a}(y+a) \times \left(\sum_{m=-\infty}^{\infty} M_{2m+1}e^{i(2\pi/L)(2m+1)z}\right) \times \left(\sum_{k=-\infty}^{\infty} J_k(\Gamma L)e^{i(4\pi k/L)z}\right)e^{i\beta_0 z} \qquad (78)$$

from which we obtain, in turn (see Table 1 for a summary of the coefficients)

$$E_z = \frac{i\omega\mu\pi H_0}{4a\gamma^2}\sin\frac{\pi}{2a}(y+a) \times \sum_{n=-\infty}^{\infty} N_n e^{i\beta_{2n+1}z} \qquad (79)$$

where the relative amplitude factor N_n may be written

$$N_n = M_1J_n(\Gamma L) + \sum_{m=1}^{\infty} M_{2m-1}J_{n+m}(\Gamma L) + M_{2m+1}J_{n-m}(\Gamma L) \qquad (80)$$

and where

$$\beta_{2n+1} = \beta_0 + \frac{2\pi}{L}(2n+1). \qquad (81)$$

In particular

$$N_0 = M_1J_0(\Gamma L) + \sum_{m=1}^{\infty} M_{2m-1}J_m(\Gamma L) + M_{2m+1}(-1)^mJ_m(\Gamma L). \qquad (82)$$

Expression (79) is thus the resolution of (69) into its space-harmonic component waves. We notice that $E_z \to 0$ with l, as it should, since this component of $\mathbf{E}$ is entirely due to the bending of the guide.

Let us now consider the slightly more intricate expression (74) for the perturbed TM_{11} wave. First, rewrite (74) in the form

$$E_z = E_0\sin\frac{\pi}{2a}(y+a) \times \left[\frac{1}{(1+\sigma^2)^{1/2}}\sin\frac{\pi}{2b}\left(b+\frac{x}{(1+\sigma^2)^{1/2}}\right) \times \frac{1}{\left(1-l^2\sin^2\frac{2\pi}{L}z\right)^{1/2}} - \frac{i\beta\pi}{2b\gamma^2} \times \cos\frac{\pi}{2b}\left(b+\frac{x}{(1+\sigma^2)^{1/2}}\right)\frac{\cos\frac{2\pi}{L}z}{\left(1-l^2\sin^2\frac{2\pi}{L}z\right)^{1/2}}\right] \times \cos\left(\Gamma_1\cos\frac{2\pi}{L}z\right)e^{i\beta s(z)} \qquad (83)$$

where $\Gamma_1 = \pi A/2b(1+\sigma^2)^{1/2}$. In addition to the Fourier developments just given, we must also expand

$$\left(1 - l^2 \sin^2 \frac{2\pi}{L} z\right)^{-\frac{1}{2}} \quad \text{and} \quad \cos\left(\Gamma_1 \cos \frac{2\pi}{L} z\right).$$

Now

$$\left(1 - l^2 \sin^2 \frac{2\pi}{L} z\right)^{-\frac{1}{2}} = \sum_{n=0}^{\infty} P_n \cos \frac{4n\pi}{L} z$$

which we can write in the exponential form

$$\tfrac{1}{2} \sum_{n=-\infty}^{\infty} P_n e^{i(4n\pi/L)z}$$

provided that in the latter expression we double the value of P_0 and set $P_{-n} = P_n$ ($n = 1, 2, 3, \cdots$). Expressions for P_n will be found in Table 1. For the second expression, Watson ([8], page 22) gives us

$$\cos\left(\Gamma_1 \cos \frac{2\pi}{L} z\right) = \sum_{n=-\infty}^{\infty} (-1)^n J_{2n}(\Gamma_1) e^{i(4\pi n/L)z}.$$

Then

$$\cos\left(\Gamma_1 \cos \frac{2\pi}{L} z\right) e^{i\beta s(z)} = e^{i\beta_0 z} \sum_{k=-\infty}^{\infty} Q_k e^{i(4\pi k/L)z}$$

where

$$\begin{aligned} Q_k &= \sum_{n=-\infty}^{\infty} (-1)^n J_{2n}(\Gamma_1) J_{k-n}(\Gamma L) \\ &= J_0(\Gamma_1) J_k(\Gamma L) + \sum_{n=1}^{\infty} (-1)^n J_{2n}(\Gamma_1) \\ &\qquad \times [J_{k+n}(\Gamma L) + J_{k-n}(\Gamma L)] \qquad (84) \\ &\qquad (k = 0, \pm 1, \pm 2, \cdots). \end{aligned}$$

Then (83) becomes

$$\begin{aligned} E_z = E_0 \sin \frac{\pi}{2a}(y + a) &\times \left[\frac{1}{2(1+\sigma^2)^{\frac{1}{2}}} \sin \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{\frac{1}{2}}}\right) \right. \\ &\times \left(\sum_{m=-\infty}^{\infty} P_m e^{i(4\pi m/L)z}\right) - \frac{i\beta\pi}{2b\gamma^2} \\ &\times \cos\left(b + \frac{x}{(1+\sigma^2)^{\frac{1}{2}}}\right) \\ &\times \left. \left(\sum_{m=-\infty}^{\infty} M_{2m+1} e^{i(2\pi/L)(2m+1)z}\right) \right] \\ &\times e^{i\beta_0 z} \sum_{k=-\infty}^{\infty} Q_k e^{i(4\pi k/L)z} \end{aligned}$$

where β_0 is again given by (77), but β now has the value $[k^2 - (\pi/2a)^2 - (\pi/2b)^2]^{\frac{1}{2}}$. When the series in the last expression are multiplied, we obtain

$$\begin{aligned} E_z = E_0 \sin \frac{\pi}{2a}(y+a) &\times \left[\frac{1}{2(1+\sigma^2)^{\frac{1}{2}}} \sin \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{\frac{1}{2}}}\right) \right. \\ &\times \sum_{n=-\infty}^{\infty} R_n e^{i\beta_{2n} z} - \frac{i\beta\pi}{2b\gamma^2} \\ &\times \cos \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{\frac{1}{2}}}\right) \\ &\times \left. \sum_{n=-\infty}^{\infty} S_n e^{i\beta_{2n+1} z} \right] \qquad (85) \end{aligned}$$

where the coefficients R_n and S_n are themselves given by

$$\begin{aligned} R_n &= \sum_{k=-\infty}^{\infty} P_k Q_{n-k} = P_0 Q_n \\ &\qquad + \sum_{k=1}^{\infty} P_k Q_{n-k} + P_{-k} Q_{n+k} \\ S_n &= \sum_{k=-\infty}^{\infty} M_{2k+1} Q_{n-k} = M_1 Q_n \\ &\qquad + \sum_{k=1}^{\infty} M_{2k+1} Q_{n-k} + M_{-(2k-1)} Q_{n+k} \qquad (86) \\ &\qquad (n = 0, \pm 1, \pm 2, \cdots). \end{aligned}$$

The expression (85) shows in a particularly interesting way the effect of the bending on the TM_{11} wave, which we can interpret as follows: as a result of the periodic bending, the new component E_z consists of the superposition of infinitely many space-harmonic waves. These waves divide naturally into two groups which we may designate as *even* and *odd* waves depending on whether their phase-shift factors are β_{2n} or β_{2n+1}, respectively. The amplitudes of the odd waves, being proportional to l, tend to zero with the amplitude of the bend, while the even waves all "merge" into a single such wave, namely, the component of E_z in the unperturbed TM_{11} mode. One cannot but notice that the field consisting of the odd waves alone resembles the expression (79) for the TE_{10} mode, which may thus be said to consist entirely of odd waves.

6. Phase Velocity And Impedance In Bent Guide

Let us first consider the space harmonics of the perturbed TE_{10} wave (79). In the sense last discussed above, this field possesses only odd space harmonics. Their phase velocities are given by

$$\frac{v_{2n+1}}{c} = \frac{kL}{\beta_{2n+1}L} = \frac{kL}{\frac{2}{\pi}\mathrm{E}(l)(1+\sigma^2)^{1/2}[(kL)^2 - (\pi L/2a)^2]^{1/2} + (2n+1)2\pi}$$

$$(n = 0, \pm 1, \pm 2, \cdots).$$

In particular, for the *lowest-order forward wave* $(n = 0)$,

$$\frac{v_1}{c} = \frac{kL}{\frac{2}{\pi}E(l)(1+\sigma^2)^{1/2}\left[(kL)^2 - \left(\frac{\pi L}{2a}\right)^2\right]^{1/2} + 2\pi}. \tag{87}$$

The amplitude $E_z^{(1)}$ of the particular space-harmonic wave having phase-shift β_1 is

$$E_z^{(1)} = \frac{i\omega\mu\pi H_0}{4a\gamma^2}\sin\frac{\pi}{2a}(y+a)N_0 \tag{88}$$

where

$$\begin{aligned} N_0 &= M_1 J_0(\Gamma L) \\ &\quad + \sum_{m=1}^{\infty} J_m(\Gamma L)[M_{2m-1} + (-1)^m M_{2m+1}] \\ &= M_1 J_0(\Gamma L) + J_1(\Gamma L)(M_1 - M_3) \\ &\quad + J_2(\Gamma L)(M_3 + M_5) + \cdots \end{aligned}$$

If we take for N_0 the somewhat crude approximation obtained by retaining only M_1 and M_3, then

$$\begin{aligned} N_0 \cong\ & M_1[J_0(\Gamma L) + J_1(\Gamma L)] \\ & - M_3[J_1(\Gamma L) - J_2(\Gamma L)]. \end{aligned} \tag{89}$$

Expressions for M_1 and M_3 will be found in Table 1.

Considering that an amplifier employing bent guide for its delay line would use a sheet beam of rectangular cross section (Figure 12), an approximate expression for the impedance of the $E_z^{(1)}$ wave is

$$Z_1 = \frac{|E_z^{(1)}|^2}{2\beta_1^2 P} = \left(\frac{\mu}{\epsilon}\right)^{1/2}\frac{kl^2}{8ab\beta\beta_1^2}N_0^2\bar{f}(y). \tag{90}$$

In (90), we have used the expression for the power P carried by the TE_{10} wave in straight guide, namely,

$$P = ab\frac{\omega\mu\beta}{\gamma^4}\left(\frac{\pi H_0}{2a}\right)^2 \text{ watts}$$

since our fields are derived from the latter by a perturbation. $\bar{f}(y)$ is the average value of $\sin^2\frac{\pi}{2a}(y+a)$, taken over the sheet beam cross section of dimensions $2A_1 \times 2B_1$ (Figure 12). Thus

$$\bar{f}(y) = \frac{1}{2}\left(1 + \frac{a}{\pi A_1}\sin\frac{\pi A_1}{a}\right).$$

For the impedance Z_1, we therefore have the very simple formula

$$Z_1 = \left(\frac{\mu}{\epsilon}\right)^{1/2}\frac{kl^2 N_0^2}{16ab\beta\beta_1^2} \times \left(1 + \frac{a}{\pi A_1}\sin\frac{\pi A_1}{a}\right) \tag{91}$$

where N_0 is given by (89).

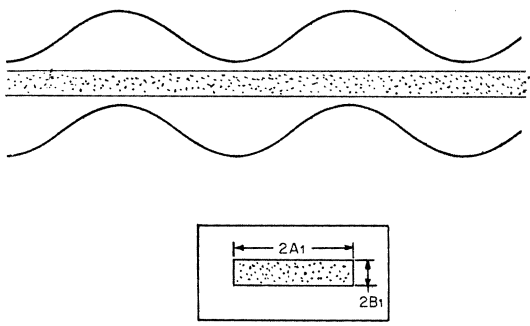

Figure 12—Disposition of a sheet beam of electrons in bent guide.

Turning next to the perturbed TM_{11} mode (85), of most interest is its space-harmonic wave of lowest order, $n = 0$. For this wave,

$$E_z^{(0)} = \frac{E_0}{2(1+\sigma^2)^{1/2}} \sin \frac{\pi}{2a}(y+a) \times \sin \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)}\right) R_0 e^{i\beta_0 z}. \quad (92)$$

In this case, although no easy approximation to R_0 is available, we still obtain a reasonably simple formula for the impedance of (92). Again calculating (by Poynting's formula) the power P carried by the unperturbed TM_{11} wave, we have for the impedance Z_0 of (92)

$$Z_0 = \frac{\overline{|E_z^{(0)}|^2}}{2\beta_0^2 P} = \left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{\left(\frac{\pi}{2a}\right)^2 + \left(\frac{\pi}{2b}\right)^2}{8ab(1+\sigma^2)k\beta\beta_0^2} R_0^2 g \quad (93)$$

where

$$g = \text{average value of } \sin^2 \frac{\pi}{2a}(y+a) \times \sin^2 \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{1/2}}\right)$$

over the beam cross-section of Figure 12

$$= \frac{1}{4A_1B_1}\int_{-B_1}^{B_1} \sin^2 \frac{\pi}{2b}\left(b + \frac{x}{(1+\sigma^2)^{1/2}}\right) \times dx \int_{-A_1}^{A_1} \sin^2 \frac{\pi}{2a}(y+a)\, dy$$

$$= \frac{1}{4}\left(1 + \frac{b(1+\sigma^2)^{1/2}}{\pi B_1} \sin \frac{\pi B_1}{b(1+\sigma^2)^{1/2}}\right) \times \left(1 + \frac{a}{\pi A_1} \sin \frac{\pi A_1}{a}\right). \quad (94)$$

With the rather crude approximation

$$R_0 \cong P_0 J_0(\Gamma_1) J_0(\Gamma L)$$

(93) and (94) may be used to obtain a preliminary estimate of the impedance Z_0 for this wave.

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21. A. L. Cullen, "The Theory of The Sinuous Waveguide Beam-Coupler for Millimeter Wave Generation," Microwave Laboratory Report 633, Stanford University; September 1959.

22. H. H. Snyder and R. W. Wilmarth, "Applied Research on a High-Power V-Band Amplifier," Technical Proposal 93302, ITT Federal Laboratories; January 1961.

23. A. Asam and J. M. Grant, "Rectangular Waveguide with Periodic Bends," Interim Technical Report on High-Power Structures, ITT Federal Laboratories; 1 December 1959.

24. A. B. Bronwell and R. E. Beam, "Theory And Application of Microwaves," McGraw-Hill Book Company, New York, 1947.

Herbert H. Snyder was born in Ravenswood, West Virginia, on 26 February 1927. He received mathematics degrees of A.B. from Marietta College and M.A. and Ph.D. from Lehigh University.

From 1953 to 1963 he was employed in the electron tube laboratory of ITT Federal Laboratories, doing research in guided wave propagation and electron beam dynamics applicable to traveling-wave tubes. Since then Dr. Snyder has been associated with the mathematics departments of Newark College of Engineering and Drexel Institute of Technology. He is now Associate Professor of Mathematics at Southern Illinois University where, in addition to teaching duties and research in pure mathematics, he continues to be interested in problems related to research in electronics.

Cryptographic Protection of Commercial Teleprinter Traffic—Used in conjunction with the standard 5-unit start-stop code teleprinter equipped with tape punch and tape reader, the Cryptel *240* machine scrambles messages before transmission and unscrambles them at the receiving end.

A set of pins inserted in holes on a panel determine the scrambling code. The positions of the pins are readily changed by nontechnical personnel as is evident from Figure 1. The number of different scrambling codes is 2.5×10^{26}. There are no moving parts with the exception of the control switches. Integrated semiconductor circuits are mounted on printed wiring boards.

The machine is 7.5 by 14 by 12 inches (184 by 355 by 305 millimeters) and weighs 21.4 pounds (9.7 kilograms).

ITT World Communications
United States of America

Telediagnosis System for Mobile Use—Sponsored by Professor Lareng and Doctor Daver, with the cooperation of the French Safety Civil Authorities, a telediagnosis system has been introduced in Europe. This initial installation operates from the medical center at Purpan-Toulouse.

Figure 1—Cryptel *240* scrambler for commercial teleprinter traffic uses pins in holes to determine the scrambling code. There are approximately 2.5×10^{26} possible settings.

During transport of an injured person in the specially equipped ambulance, transducers connected to an electronic surveillance box are attached to the patient to provide electrocardiograms and to monitor pulse beats, cardiac rhythm, respiration, blood pressure, temperature, and the rate of several reflexes. These data are transmitted immediately by radio to the medical center, where they are displayed. A doctor can use this information to direct the ambulance attendant, also by radio, in treating the patient.

The fixed and mobile very-high-frequency transmitter—receivers are of our type *3476B* and *3468B,* which are installed in almost all ambulances of the civil rescue organization and the fire protection system in France. The diagnostic boxes and hospital display units are manufactured by Électronique Marcel Dassault in France.

Le Matériel Téléphonique
France

India Inaugurates First Pentaconta Telephone Exchange—The first Pentaconta telephone exchange in India was cut over in Madras in February 1967. It provides for 5000 subscriber lines and interworks with the existing step-by-step network. The inauguration ceremonies were attended by Sardar Ujjal Singh, Governor of Madras, and for Bell Telephone Manufacturing Company by F. Pepermans, Managing Director and General Manager; P. H. Spaak, Belgian Minister of State and Director; and E. A. Van Dyck, Manager of the Switching Division.

Bell Telephone Manufacturing Company
Belgium

Aurora Lights to be Investigated by Satellite—The Kiruna Geophysical Observatory in northern Sweden has ordered from Standard Radio & Telefon high-voltage supplies and electronic counters shown in Figure 2 for use with measuring equipment to be carried by the *TD2* satellite to be launched by the European Space Research Organization. This equipment will investigate some of the still-unknown properties of the aurora lights.

The Kiruna Geophysical Observatory has a worldwide reputation as a leader in ionosphere research and in other geophysical areas. It has long investigated ionosphere phenomena observed at high latitudes.

The experiment will consist of measuring the energy level and angle of incidence of the electrons and protons generating the aurora lights. An important part of the design, made by the observatory, is the electrostatic measuring probes for catching these particles and making these tests during the time the satellite is orbiting a polar region.

A similar set of equipment will be supplied to the Observatory for inclusion in ESRO 1, an 85-kilogram (187-pound) satellite in the series of small satellites under development by the European Space Research Organization.

Standard Radio & Telefon
Sweden

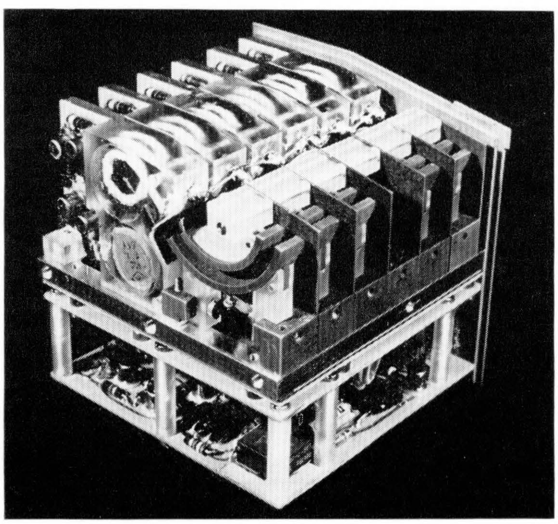

Figure 2—High-voltage generator and particle detector for ESRO 1.

Phase Computing System for Radar—Special-purpose computing techniques developed for learning machines have been applied to digital radar systems.

A joint study with Standard Radio & Telefon (Sweden) of its digital plan position indicator has shown that the azimuth sweep generator may be constructed in integrated circuits using computer techniques developed at our laboratories. In addition, facilities for the rectangular-to-polar conversion of the coordinates of an adjustable marker may be added to the plan-position-indicator console to enable the operator to read out the range and bearing of any marked point.

A prototype phase computing system, as illustrated in Figure 3, is being constructed and will include facilities for radar-echo simulation and the realization of smoothing and predicting equations for automatically tracking radar targets.

Standard Telecommunication Laboratories
United Kingdom

Pulse Coherent Doppler Radar—Pulse coherent Doppler radar improves the detection of small moving targets by suppressing the clutter return from the stationary target environment. Much improvement over the original moving-target-indicator system, particularly in the suppression of clutter,* has resulted from more-effective filter circuits.

In the surveillance mode existing radars use a limited number (5 to 10) of range gates to cover the entire range, and a single wide-band Doppler filter to cancel the clutter echoes. This severely limits scanning rate and sensitivity. The bandwidth of the Doppler filter is many times larger than the line width of the received echo spectrum, and for best signal-to-noise ratio between 10 and 50 filters should be available

* "Battlefield Surveillance Radar," *Electrical Communication,* volume 40, number 1, pages 8–9; 1965.

for each range gate. As between 100 and 1000 range gates are needed for maximum information rate, a total of 1000 to 50 000 Doppler filters would be required for the best receiver.

A new filtering process proposed by Chief Engineer Albagli of Génie Maritime presented technical difficulties that have been overcome through the use of digital techniques. It requires only one Doppler filter for all range gates by means of time compression using a memory in which the received signals are stored.

This special equipment shown in Figure 4 and consisting of an analog-to-digital converter, a large-capacity core memory, a decoder, and a Doppler filter was built under contract for the Direction des Recherches et Moyens d'Essais. It is being tested with an existing radar under contract for Direction des Études et Fabrication d'Armement (Section d'Études et Fabrication des Télécommunications).

Preliminary laboratory tests indicate the following improvement with respect to the earlier moving-target radars. Scanning time for 180 degrees and 10-kilometer range is reduced from 22 to 4 seconds, clutter cancellation is increased from 40 to 50 decibels, maximum range on small targets is increased by 60 percent (for example, 10 to 16 miles). The new system also provides indication of radial speed of target motion not available with the earlier radars. The reduced bandwidth of the receiver makes it less sensitive than the old to jamming.

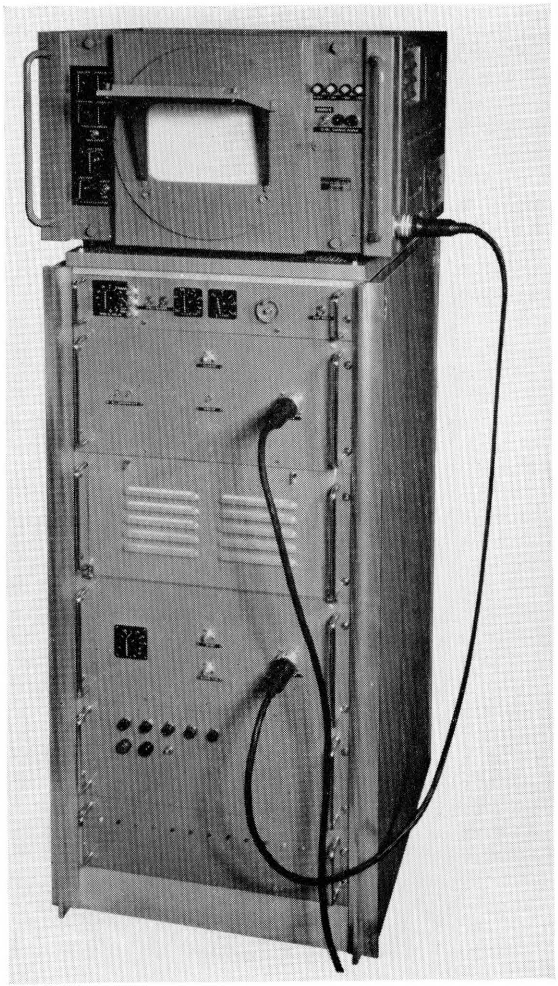

Figure 4—Equipment for the improved processing of information from a pulse coherent Doppler radar.

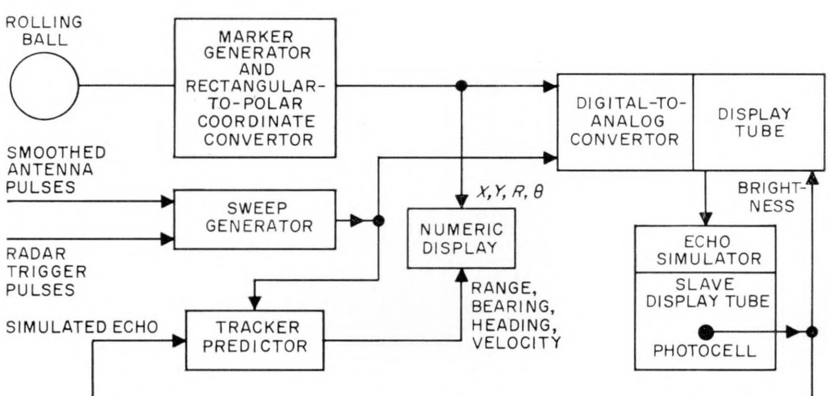

Figure 3—Prototype phase computing system for radar.

The digital process gives the coordinates, range, and speed of the detected target in binary form for direct transfer to a computer, performing the functions of a matched-filter receiver and information extractor.

Laboratoire Central de Télécommunications
France

Satellite Television Relay Across Pacific—The first commercial television programs from the United States to Japan via Lani Bird, the communication satellite hovering over the Pacific Ocean, were transmitted on 27 and 29 January 1967. The initial program, a 12-minute round-up of United States news, was transmitted in full color from the studios of the National Broadcasting Company in New York to the Nippon Television Network Corporation, the sponsor of the program.

ITT World Communications
United States of America

Track-Diagram Installation Replaces 8 Railroad Signal Towers—A track-diagram railroad track switching system installed in Oldenburg, Germany, replaces 8 conventional signal towers. At the crossing of the north-south rail line between Wilhelmshaven and Muenster and the east-west line between Bremen and Emden, this installation serves 400 trains with 2000 switching operations per day. Only two operators are required. The operating desk, shown in Figure 5, controls 165 track switches, 32 main-line blocking and clearing signals, 116 other blocking signals, and 56 miscellaneous light signals.

Standard Elektrik Lorenz
Germany

Power Supply for Traveling-Wave Tubes—A recently developed power supply is suitable for use with all traveling-wave tubes in the 4-to-15-gigahertz range made by Standard Telephones and Cables (United Kingdom). Close supervision and alarms for collector, helix, and

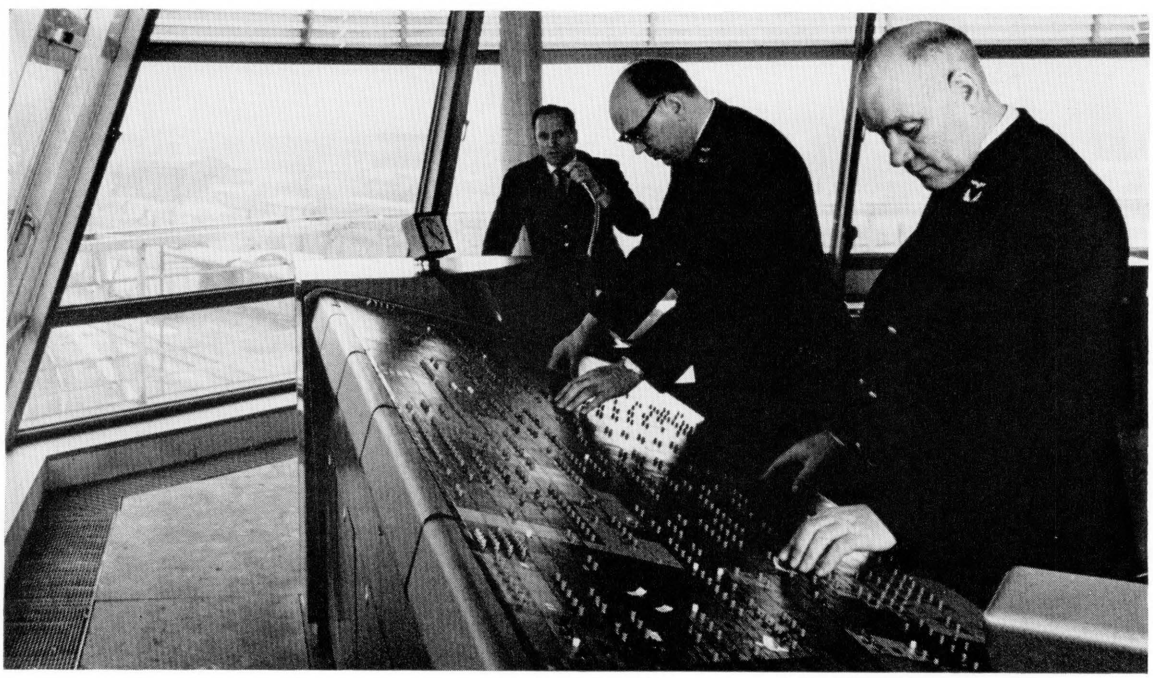

Figure 5—Operating desk at Oldenburg, Germany, of track-diagram railroad switching installation.

cathode-heater supplies are featured. The unit is operable to 3500 meters (11 500 feet) above sea level, evidence of excellent insulation.

In Figure 6, the indicating instrument is connected to various circuits through the switch to its left. There are 3 alarm lights beneath the instrument and a reset button to their left. The various output levels are determined by the 3 controls at the right.

Operated from a 220-volt 50-hertz supply, the collector voltage may be adjusted between 1400 and 2000 volts at 100 milliamperes, the helix supply between 2300 and 2800 volts at 2 milliamperes, and the heater voltage between 5.8 and 6.8 volts at 0.5 and 1.5 amperes. Constructed to ITT Europe standard equipment practice, the dimensions are 445 by 425 by 215 millimeters (17.5 by 16.8 by 8.5 inches) and the weight is 39 kilograms (86 pounds).

Standard Téléphone et Radio
Switzerland

Digitor Remote Alarm System—The Digitor *400* system will monitor fire sprinklers, fire alarm boxes, watchman tour stations, smoke detectors, thermostats, limit sensors, and all types of burglar alarms from a central installation shown in Figure 7. Each of the basic monitor consoles shown has a capacity of 100 circuits. Supervision can be provided for heating and air-conditioning systems, control equipment, flow regulators, motors, pumps, compressors, fans, liquid levels, refrigerator systems, et cetera.

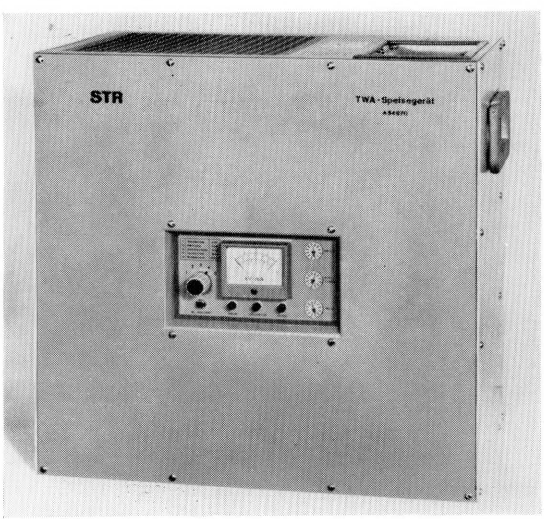

Figure 6—Power supply for traveling-wave tubes.

Completely electronic and with solid-state components, it will monitor up to 1000 detection circuits, each of which can include more than one detection device, at a rate of 10 to 15 circuits per second. The first such system to use multiplex techniques, no single alarm can block other signals even if 1000 alarms occur simultaneously. The operator can control or test remote equipment without interfering with the monitoring capability at the same location.

Changes indicated by the detectors operate an audible signal at the console and are recorded permanently by printout. An alarm is repeated until acknowledged by the operator and the acknowledgment also is recorded. The transmission system is designed for fail-safe operation.

ITT Mackay Marine Division
United States of America

Pulse-Code-Modulation Telephony for Finland—Two 24-circuit pulse-code-modulation telephone systems are being built for the Helsinki Telephone Company. This is the first such

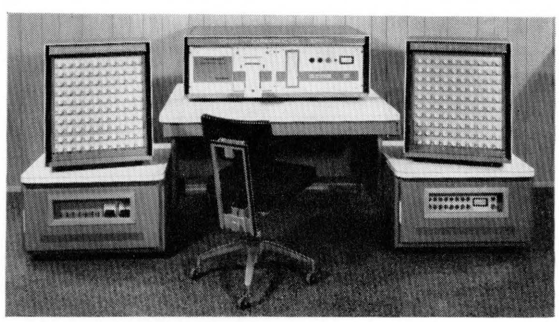

Figure 7—Console flanked by two 100-circuit indicator panels of the Digitor *400* multiplex alarm monitoring and recording system.

equipment to be exported from the United Kingdom to Europe. A complete 24-circuit 2-way repeater is shown in Figure 8. These repeaters completely regenerate the received signals to suppress noise. The number of circuits that can be transmitted over existing audio pairs in underground cable is greatly increased by using pulse code modulation.

Standard Telephones and Cables
United Kingdom

Radar Simulators—The first of three radar simulators to be used with our flight simulators for the *Mirage III* military jet aircraft has been shipped to the United States, where it will be coupled to a special video generator built by the Link Division of General Precision Incorporated. Both the radar and flight simulators are housed in their own semitrailers and are interconnected by cables. The new equipment will extend the original flight simulation to include simulation of air-to-ground modes of the French *Cyrano IIB* radar. One radar unit has been ordered by the French Air Force and two by the Royal Australian Air Force.

Le Matériel Téléphonique
France

Figure 8—Complete 24-circuit 2-way repeater for pulse-code-modulation telephony.

Mail Sorter Handles 21 600 Letters Per Hour—A trial installation of a letter sorting system capable of handling 21 600 letters per hour has been placed in operation at the central post office in Wiesbaden, Germany.

After other machines have selected all the letters suitable for automatic processing, have arranged them face up with the addresses in proper position for reading, and have automatically cancelled the stamps, the letters go to the coding desks and the distribution machine built by Standard Elektrik Lorenz and shown in Figure 9.

At each coding position the operator can print the zip code in fluorescent marks in the lower right corner on 5000 envelopes per hour. After coarse sorting into "foreign countries," "own town" and "unsuitable for coding," the letters are mechanically conveyed to the distributing machine that can handle 21 600 letters per hour.

Figure 9—Coding desks in Wiesbaden postoffice for marking letters in fluorescent ink. These marks actuate electronic readers to determine the destination boxes into which the distributing machine behind the operators sorts the letters.

The distributing machine employs modules of 20 destination boxes each. The Wiesbaden installation has 100 destination boxes and can be extended to 200 boxes. An electronic reader operated by the fluorescent marks controls the distribution of each letter to the appropriate box.

Standard Elektrik Lorenz
Germany

Main Distributing Frame In Miniature Size—A main distributing frame for telephone exchanges has been developed in greatly reduced size. The disconnect jacks associated with the exchange cabling use 33-point connectors built to the ITT Europe standard equipment practice as shown in Figure 10. They are mounted in several vertical arrays that accommodate 1000 lines in the upper part of a frame. In the lower part of the frame are corresponding terminal arrays mounted back to back, these terminals being connected to 1600 cable pairs. Between the two sets of terminal arrays is a horizontal area through which the jumpers run in bundles.

Printed-circuit keys are locked in the 33-point jack and provide either for through connection of the *a,b* and *a′,b′* wires or for test, cutoff, or special line conditions. Protectors can be plugged to the incoming terminal arrays.

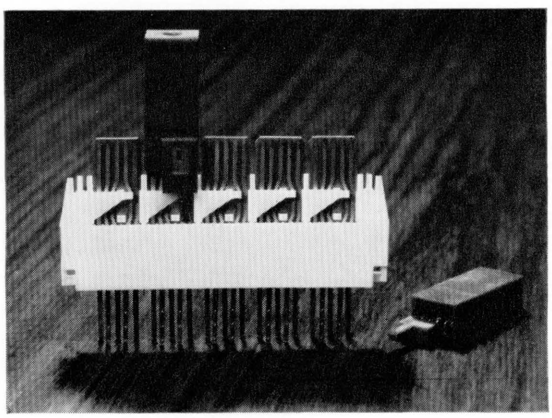

Figure 10—Disconnect keys shown with contacts for the miniature main distributing frame.

The new design reduces floor space by 70 percent, reduces jumper-wire length by 45 percent, provides an important saving in installation cable and installation time, and—being of modular design for 4000 or 10 000 lines—provides flexibility for installations up to 50 000 lines. Jumpering uses wrapped connections and is done at floor level by a single worker. Tracing of jumper wires is easier than with conventional construction. A wall main distributing frame based on the same construction and wiring principles is also provided.

Bell Telephone Manufacturing Company
Belgium

London Telex Exchange—A new London telex exchange in Houndsditch in the City of London will include automatic switching equipment for 8000 subscribers, 2700 national, and 3400 international trunk circuits. The new *C* signaling system of the International Telegraph and Telephone Consultative Committee (CCITT) will be used for transit calls, and the *A* and *B* systems will be used to interwork with countries now using these systems.

Standard Telephones and Cables
United Kingdom

Television Transmitters for Second Program in Austria—The television transmitter network for the second program in Austria is being extended. A new transmitter with a picture output of 20 kilowatts and a sound output of 2 kilowatts was installed on the Gaisberg, near Salzburg. With the antennas provided, the effective radiation is 1000 kilowatts. It may be remotely controlled. A similar installation will be made in the Schoeckl mountain near Graz.

Standard Elektrik Lorenz
Germany

V-Belt Conveyor for Swissair—While pneumatic tube systems require carriers, a V-belt conveyor avoids the carrier by moving documents of various dimensions upright along metal channels. Endless belts are driven at speeds between 0.8 and 1.2 meters (2.6 to 3.9 feet) per second, the number of belts being determined by the number of conveyor channels and directions.

Figure 11 shows a multichannel conveyor recently installed for the Swissair Central Administration (Final Booking) at Kloten Airport. The 15 operator positions are reached by 15 channels from a distributing center. Return dispatches are made via collecting channels. The charter documents reach the collecting channels through slots in the tables.

The total length of the conveyor belts is 820 meters (2690 feet) and the length of the side guides amounts to 586 meters (1920 feet). A single motor drives the 15 distributing tracks and 13 smaller drives are for the lateral and main collecting channels.

Standard Téléphone et Radio
Switzerland

Sonar Data Recording—A new shipboard sonar data recorder shown in Figure 12 has been delivered to the United States Naval Underwater Sound Laboratory.

The system records the output from a sonar transducer on a continuous loop of tape that provides 20 or 40 seconds of delay for evaluation and transfer to a permanent tape. Voice commentary may be added to the permanent tape.

ITT Federal Laboratories
United States of America

Figure 11—V-belt conveyor system for Swissair at Kloten airport.

Television Chrominance Delay Line—The chrominance delay line required by the Phase Alternation Line system of color television must have excellent stability as a function of temperature. A recent design uses annealed iron-nickel-chromium alloy in a strip 200 by 15 by 0.25 millimeters (7.9 by 0.6 by 0.01 inches) weighing 6 grams (0.2 ounce). The average delay of 64 microseconds varies by only ± 3 nanoseconds over the range from 20 to 50 degrees Celsius. The insertion loss is 10 decibels with an output impedance of 2000 ohms. The pass band is 2.6 megahertz.

Laboratoire Central de Télécommunications
France

Pneumatic Tube System With High Carrier Speed—A pneumatic tube system has been installed in the Mannesmann Steel Works to transport red-hot steel samples weighing 300

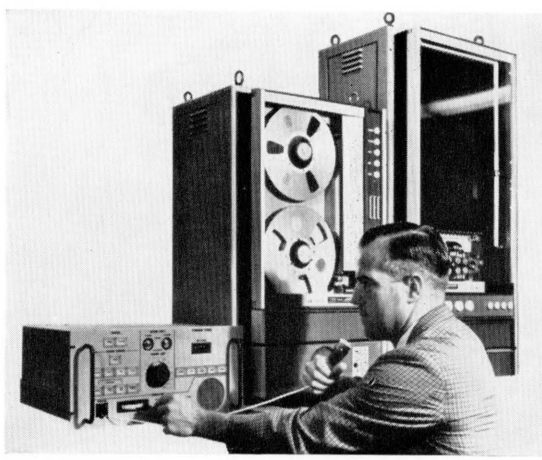

Figure 12—Sonar data recorders. The two tall cabinets house magnetic tape recorders and the smaller cabinet holds the control equipment.

grams (10.6 ounces) for a distance of 2.5 kilometers (1.6 miles) to the central laboratory for immediate analysis. A carrier speed of 40 meters (130 feet) per second is featured, as operations are interrupted until the analysis is completed. Conventional pneumatic tube systems require about 4 minutes contrasted with 1 minute for this high-speed system.

The long pneumatic tube receives air at several equally separated places with the rate of air flow adjusted to the carrier speed at that section. This permits rapid increase of speed at the start and controlled reduction in speed near the destination. Final braking is by the opposing pressure of the air in the terminating section. A station is shown in Figure 13.

Standard Elektrik Lorenz
Germany

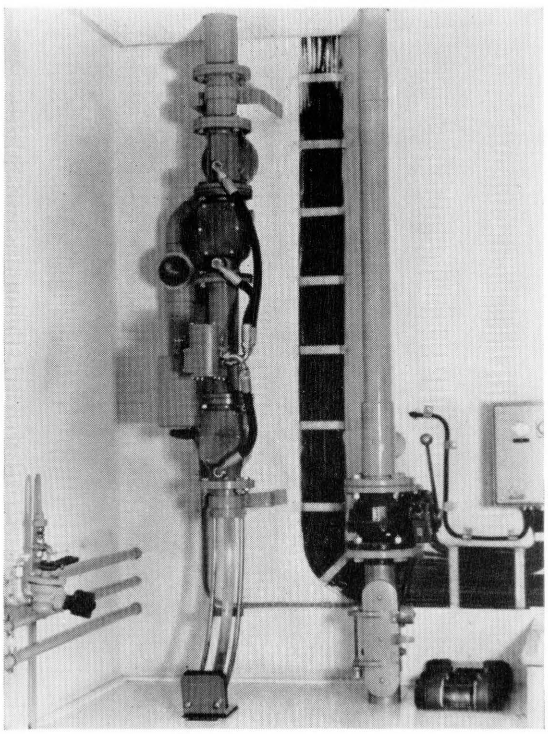

Figure 13—Transmitter (right) and receiver (left) of the long high-speed pneumatic tube system for transporting steel samples.

Crossbar Transit Centers at Birmingham and Leeds—As shown in Figure 14, Pentaconta crossbar telephone switching equipment is being manufactured for installation in transit switching centers in Birmingham and Leeds. The *BXB1100* system will use high-speed multifrequency interexchange signaling.

Standard Telephones and Cables
United Kingdom

High-Frequency Radio Equipment for Colombia—Now being constructed for Empressa Nacional de Telecommunicaciones for installation at El Rosal in the Bogota plateau are five 30-kilowatt *QT8* and five 3-kilowatt *QT2* autotune radio transmitters with drive units of both frequency-synthesizer and independent-sideband types. Log periodic aerials for horizontal and vertical polarization will include automatic coaxial switching to the transmitters.

The five autotune receivers *RX11* with control facilities to operate with log periodic antennas will be at San Juan, east of Bogota, and both

Figure 14—Operator using preset-torque pneumatic screwdriver in assembling crossbar telephone switches.

transmitting and receiving will be under control of a single operator. This high-frequency installation will be used for international telephony and telegraphy.

Standard Telephones and Cables
United Kingdom

Telephone Subscriber Loudspeaker—The type *700* unit shown in Figure 15 comprises a transistor amplifier with internal 9-volt battery, a loudspeaker, and a volume control with on-off switch. It may be added to any telephone subscriber set to permit additional people to hear the distant subscriber and as an aid in overriding noise.

Standard Elektrik Lorenz
Germany

Measurement Instruments—A number of new measurement instruments have been announced.

(A) *Digital Multimeter DX603A:* In addition to the usual voltage and resistance measurements, the *DX603A* measures capacitance, frequency (time), and counts pulses. Plug-in units are provided for each function.

Measured values are displayed to 3 significant figures. The full-scale values for direct voltage are from 0.1 millivolt to 1000 volts, resistance measurements are between 0.001 ohm and 1000 megohms, and capacitance is between 1 picofarad and 10 000 microfarads.

Frequencies are measured up to 1 megahertz.

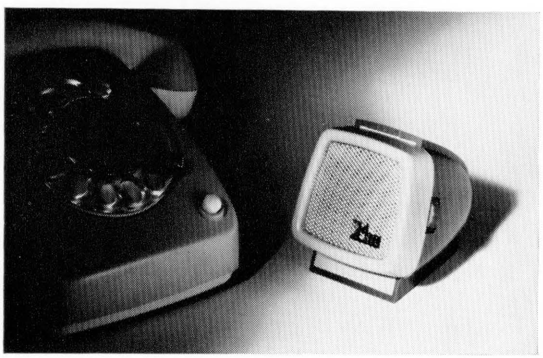

Figure 15—Loudspeaker with built-in amplifier and battery for use with a telephone subscriber set.

Time is measured from 100 milliseconds to 1000 seconds. Pulses are counted up to 6 figures or to 9 figures with a special plug-in unit. Pulse repetition rates range up to 10^6 per second or to 10^{3n} per second with n plug-in units.

The basic unit, into which function units may be plugged, has dimensions of 162 by 234 by 327 millimeters (6.4 by 9.2 by 12.9 inches) and the weight is 4.5 kilograms (10 pounds).

(B) *Audio-Frequency Generator GX204A:* This instrument generates all frequencies between 15 hertz and 160 kilohertz with a direct-reading scale accurate to within 3 percent. Harmonic distortion does not exceed between 1 and 3 percent depending on the frequency range. It incorporates the usual facilities including an output attenuator. Dimensions are 150 by 185 by 290 millimeters (5.9 by 7.3 by 11.4 inches) and weight is 4.5 kilograms (10 pounds).

(C) *Impedance Bridge IX307A:* Resistance, capacitance, and inductance, as well as Q and tan δ, are measured with this bridge. Typically, resistance measurements are within 1 percent from 0.1 ohm to 1 megohm and within 2 percent up to 10 megohms. Dimensions are 445 by 220 by 287 millimeters (17.5 by 8.7 by 11.3 inches) and weight is 16 kilograms (35 pounds).

(D) *Portable Microammeter MX309A:* This direct-current instrument has 13 ranges from 1 microampere to 10 amperes and to 300 amperes with an external shunt. Accuracy is within 1.5 percent of full-scale deflection. Accessories provide for temperature measurement. Dimensions are 220 by 170 by 120 millimeters (8.7 by 6.7 by 4.7 inches) and weight is 1.95 kilograms (4.3 pounds).

(E) *Electronic Millivoltmeter VX207A:* This general-purpose meter covers a range from 1 millivolt to 30 volts, root mean square, from 10 hertz to 1 megahertz. The accuracy is within 3 percent of full-scale deflection for a 9-volt power supply and within 5 percent for a lower voltage. Dimensions are 220 by 227 by 180 millimeters (8.7 by 8.9 by 7 inches) and weight is 5 kilograms (11 pounds).

(F) *Electronic Voltohmmeter VX304A:* Shown in Figure 16, this instrument has 11 direct-current ranges from 10 millivolts to 1000 volts, with alternative center zero with half these values each side of zero. For alternating current there are 8 ranges from 100 millivolts to 300 volts. Another 8 ranges for resistance cover from 0.5 ohm to 5000 megohms. Typical accuracy is within 3 percent of full-scale deflection. It can be used as an electrometer with an input impedance of 10^{12} ohms and as a memory instrument for voltage comparison. Dimensions are 220 by 221 by 212 millimeters (8.7 by 8.7 by 8.3 inches) and weight is 6.5 kilograms (14.3 pounds).

(G) *Electronic Multimeter VX306A:* This multimeter uses field-effect transistors. Ranges from 100 millivolts to 1000 volts direct current are available, and with half these values each side of a center zero. Direct-current ranges are from 1 microampere to 100 milliamperes. Resistance ranges are from 0.5 ohm to 5000 megohms. Alternating voltages and high direct voltages can be measured with accessory probes. Typical accuracy is within 3 percent. Dimensions are the same as for *VX304A*. Weight is 5.5 kilograms (12.1 pounds).

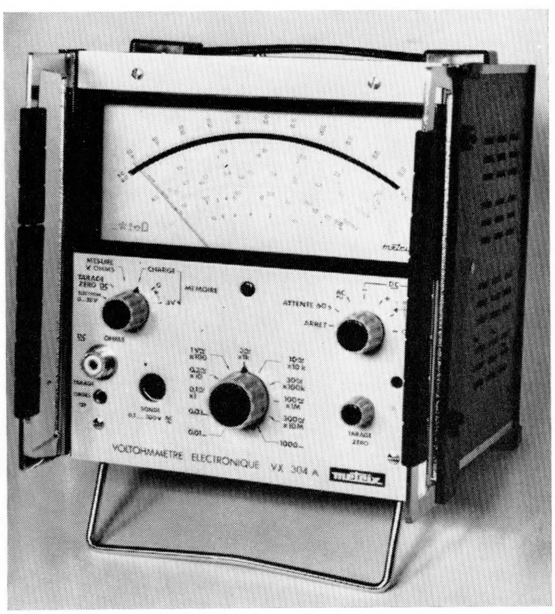

Figure 16—Electronic voltohmmeter *VX304A*.

(H) *Sweep Generator WX501A:* This sweep generator covers from 15 kilohertz to 15 megahertz with adjustable excursion at sweep frequencies between 0.25 and 75 hertz. Dimensions are 148 by 177 by 264 millimeters (5.8 by 7.0 by 10.4 inches) with a weight of 7.6 kilograms (16.8 pounds).

Compagnie Générale de Métrologie
France

Vacuum Relay—The single-pole double-throw vacuum relay shown in Figure 17 will interrupt 1000 watts of direct-current power for 100 000 operations at a maximum of either 1 ampere or 2000 volts. It will withstand a peak test voltage of 4000 volts and carry 4 amperes, root mean square, at 16 megahertz. Contact resistance will not exceed 0.010 ohm. Maximum time for operation is 10 milliseconds.

The unit occupies less than $\frac{1}{3}$ cubic inch (6 cubic centimeters) and weighs $\frac{3}{4}$ ounce (20 grams).

ITT Jennings
United States of America

Teletypesetter for Newspapers—*TF801* super-audio telegraph equipment operates over a 30-mile (48-kilometer) leased line that connects

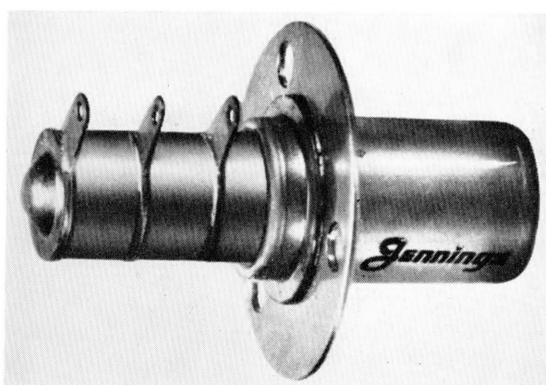

Figure 17—Compact vacuum single-pole double-throw relay capable of interrupting a kilowatt of direct-current power.

the Yorkshire Evening Post in Leeds with the Doncaster Evening Post. Tapes punched in Leeds produce replica tapes in Doncaster that are used immediately to operate typesetting machines. About 20 newspaper columns of material can be sent each day. The *TF801* also allows signals from a picture scanning machine to be transmitted simultaneously. Alternatively, the picture channel can be used for speech.

Standard Telephones and Cables
United Kingdom

Communication System for British Gas Board—An integrated radio communication system to facilitate control of a high-pressure gas pipeline supplying a number of towns is being constructed for the East Midlands Gas Board. Telemetering signals from pumping stations, gas works, and main distributing points are continuously scanned and transmitted over a 450–470-megahertz radio system from a number of main radio stations connected by a 1500-megahertz multichannel link to the central control station. Provision is also made for 2-way radio communication with mobile units maintaining the pipeline.

Standard Telephones and Cables
United Kingdom

Relay Type 26—The type *26* relay shown in Figure 18 will switch alternating currents up to 1500 voltamperes with maximums of 10 amperes or 440 volts and direct currents of 70 watts at maximums of 100 volts or 10 amperes. The volume is less than 3 cubic inches (49 cubic centimeters) and weight less than 3 ounces (85 grams).

Contacts are of silver cadmium oxide. Minimum clearance between conducting parts not electrically connected together is 0.15 inch (4 millimeters) to provide a dielectric strength of 2000 volts alternating current; other features are glass-filled alkyd contact board with good outgassing and track-resistant properties, and coil insulation of BS 2575:56 class *E*.

Coils are wound with polyurethane-insulated wire and can be provided for alternating-current operation at 240 or 110 volts or for direct-current operation at 12 to 48 volts. Terminals will take solder leads or removable AMP 0.110 Faston connectors.

Standard Telephones and Cables
United Kingdom

Intervalometer for Rocket Launchings—A solid-state intervalometer has been developed to control automatically the firing of rockets from a helicopter. It is designed to time rocket launchings so that the helicopter experiences minimum reaction forces during the fastest possible firings.

ITT Industrial Products Division
United States of America

Pentaconta Switching for Colombia—Colombia has joined the long list of countries to use the Pentaconta crossbar telephone switching system. Medellin, with over half a million population, will equip 4 urban exchanges: Buenos Aires, Alpujarra, San Bernardo, and Castilla, with this system.

Compagnie Générale de Constructions Téléphoniques
France

Milliwatt Test Set of Pocket Size—The *74311-A* milliwatt test set shown in Figure 19 uses a moving-coil indicating instrument calibrated from + 1 to − 1 decibel in 0.25-decibel divisions. For self-calibration, sectors are marked for checking the battery voltage and the input

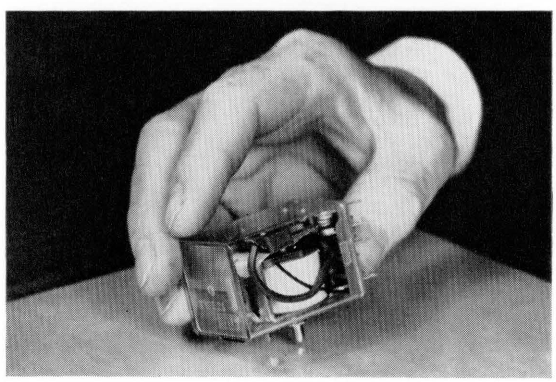

Figure 18—Type *26* relay.

return loss, which latter must be done after fitting a new thermocouple. With internal calibration, measurements at 0 decibels at 100 kilohertz on a 75-ohm circuit between 0 and 40 degrees Celsius are accurate to within 0.25 decibel, and at other frequencies up to 30 megahertz, to within 0.35 decibel. Measurements may be made up to 300 kilohertz on 600 ohms and the instrument may be adapted to 125- and 140-ohm circuits.

Powered by a single dry cell, the set is intended for field use where robustness is more important than high accuracy. Push-button switches are provided. The handle can be rotated and locked in any position to support the instrument at a convenient angle. Dimensions are 8 by 6 by 3.63 inches (20 by 15 by 9 centimeters) and the weight is 4.5 pounds (2 kilograms).

Standard Telephones and Cables
United Kingdom

Aluminum Die-Cast Boxes—Our Electronic Services Division has added to its stock a series of die-cast aluminum boxes. As shown in Figure 20, the covers provide extra screening at the edges. The 5 sizes are compatible with the ITT Europe Standard Equipment Practice modular design and range from 11.5 by 9.2 by 3.8 centimeters (4.5 by 3.6 by 1.5 inches) to 26 by 16.5 by 6 centimeters (10.2 by 6.5 by 2.4 inches).

Standard Telephones and Cables
United Kingdom

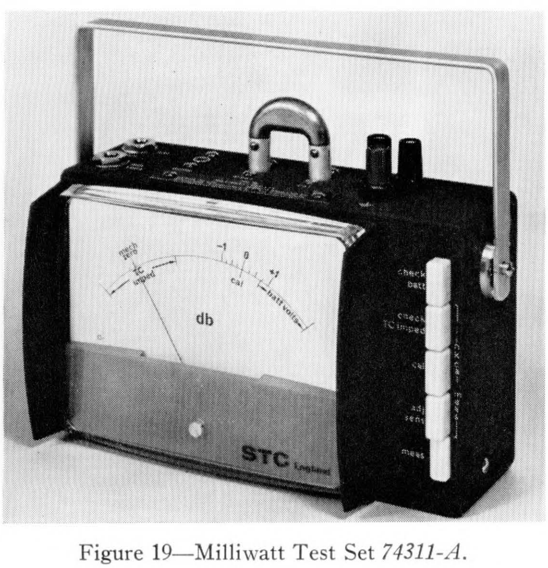

Figure 19—Milliwatt Test Set *74311-A*.

Hi-G Relays—Hi-G Incorporated, in the United States, has licensed manufacture of their miniature hermetically sealed devices for the United Kingdom market. These relays are capable of withstanding the severe environmental shocks encountered in military and aerospace applications. They include single and multiple relays in half-crystal and double-crystal size cans capable of switching direct currents of up to 10 amperes at 30 volts at sensitivities of 12 milliwatts. Also included are relays with fixed or adjustable operating delays and phase-sensing units for 3-phase systems.

Standard Telephones and Cables
United Kingdom

Russia Receives Capacitors from France—During 1967 Le Matériel Téléphonique will deliver 1 650 000 television-type electrolytic capacitors to the Union of Soviet Socialist Republics. This follows a previous delivery of 500 000 units during 1966 and is the largest order for such components ever received in France.

Le Matériel Téléphonique
France

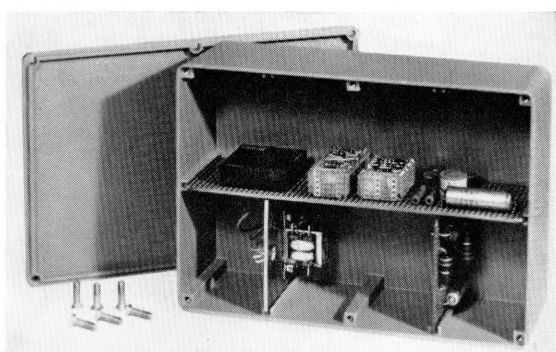

Figure 20—Die-cast aluminum box available to experimenters illustrating means of supporting equipment assemblies.

United States Patents Issued to International Telephone and Telegraph System; May–July 1966

Between 1 May 1966 and 31 July 1966, the United States Patent Office issued 64 patents to the International System. The names of the inventors, company affiliations, subjects, and patent numbers are listed below.

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R. S. Bailey, A. Senchak, S. Silverschotz, and E. McWhirter, ITT Federal Laboratories, Transmission System for Imprinted Intelligence, 3 261 911.

D. R. Barber, Standard Telecommunication Laboratories (London), Signal Amplitude Coders, 3 262 107.

J. Battista, ITT Kellogg, Electronic Circuit Breakers, 3 259 803.

H. Benmussa, Compagnie Générale de Constructions Téléphoniques (Paris), Error Eliminating Code Transmission System, 3 250 998.

H. Benmussa, P. R. L. Marty, and S. Kobus, Compagnie Générale de Constructions Téléphoniques (Paris), Pentaconta Semi-Electronic Telephone System, 3 249 698.

J. M. Blackhall, ITT Kellogg, PPCS Toll Ticketing System, 3 261 917.

R. F. Bogaerts and J. Vanderheyden, Bell Telephone Manufacturing Company (Antwerp), Fuse Protection System With an Auxiliary High Current Voltage, 3 262 018.

L. R. Bouty, Compagnie Générale de Constructions Téléphoniques (Paris), Impulse Shape Regenerating Circuit, 3 258 615.

F. H. Bray and F. Ambrosino, Standard Telephones and Cables (London), Electrical Pulse Arrangements, 3 260 800.

F. Buchwald, Standard Elektrik Lorenz (Stuttgart), Arrangement for Individually Extracting Flat Items from a Conveyor System, 3 253 825.

O. Burlak, ITT Federal Laboratories, Shift Register Employing an Energy Storage Means for Each Four-Layer Diode in Each Stage, 3 258 614.

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B. G. Coetsee, ITT Telecommunications, Time of Event Recorder, 3 262 103.

G. A. Deschamps and M. Press, ITT Laboratories, Attitude Computer with Rotatable Reference Frame, 3 258 226.

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J. Froom, Standard Telecommunication Laboratories (London), Waveguide Coupler for a Traveling Wave Tube Employing Slow-Wave Structure, 3 252 114.

J. Froom, Standard Telecommunication Laboratories (London), Slow Wave Structure for Travelling Wave Tubes, 3 258 722.

D. B. Gardner, ITT Bell & Gossett Hydronics, Pressure Relief Valve Having Auxiliary Reactor Surface, 3 254 668.

F. Gee-Wah, F. B. Cope, and R. A. Marsh, Standard Telephones and Cables (London), Cable Conductors Having a Material Binder, 3 261 906.

W. F. Glover and J. G. Bendall, Standard Telephones and Cables (London), Adjustable Inductor, 3 262 079.

J. Grambow, Standard Elektrik Lorenz (Stuttgart), Phase-Inversion Circuit, 3 258 708.

R. P. Granada and V. N. Lawford, Barton Instrument Corporation, Pneumatic Transmitter with Improved Control Mechanism, 3 262 463.

R. D. Grayson, General Controls Corporation, System for Controlling Degree of Stratification in Hot Water Heaters, 3 258 005.

W. Grobe, Standard Elektrik Lorenz (Stuttgart), Magnetic Latching Relay, 3 263 134.

R. W. Hansen, Jennings Radio Manufacturing Corporation, Vacuum Variable Capacitor, 3 257 590.

P. E. Harrison and H. Comlossy, ITT Cannon Electric, Electrical Connector Structure, 3 253 250.

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Verstraelen, R., "Digitale Bouwstenen in de Automatizering," Kring van de BRT-Labotechnici, Brussels; 28 February 1967. (Bell Telephone Manufacturing Company, Belgium)

Vidondo, F., "Aplicaciones de los Ordenadores en Telefonia," Escuela Técnica Superior de Ingenieros de Telecomunicación; March 1967. (Standard Eléctrica, Spain)

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Weir, D. A., "Electronic Switching—A Review," ITT Symposium, Lisbon; 10–14 April 1967. (Standard Telecommunication Laboratories, United Kingdom)

Widl, E., "Der Latente Reduktionsfaktor von Fernmeldekabeln," *Nachrichtentechnische Zeitschrift,* volume 19, number 12, pages 713–718; 1967. (Standard Elektrik Lorenz, Germany)

Willrett, H., "Field Experience with Quasi-Electronic Switching Systems," Institute of Electrical and Electronics Engineers International Convention, New York; 23 March 1967. (Standard Elektrik Lorenz, Germany)

Wright, E. P. G., "Meeting in Geneva of CCITT Working Party XIII/2," *ITU Telecommunication Journal;* 15 March 1967. (Standard Telecommunication Laboratories, United Kingdom)

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International Telephone and Telegraph Corporation Principal Divisions and Subsidiaries

NORTH AMERICA

MANUFACTURING—SALES —SERVICE

Canada

ITT Canada Limited, Montreal, P.Q. (1946); Branches: Edmonton, Alta.; Regina, Sask.; Winnipeg, Man.
- Barton Instruments Ltd. (Canada), Calgary, Alta. (1962)
- Cannon Electric (Canada) Ltd., Toronto, Ont. (1951)
- General Controls Company (Canada) Ltd., Guelph, Ont. (1953)
- Lustra Lighting Ltd. (Canada), Toronto, Ont. (1959)
- Royal Electric Company (Quebec) Ltd., Pointe Claire, P.Q. (1958)
- Wakefield Lighting Ltd. (Canada), London, Ont. (1953)

Jamaica

ITT Standard Electric of Jamaica Ltd., Yallahs (1963)

Mexico

ITT de México, S. A. de C. V., Mexico City (1966)
- Industria de Telecomunicación, S. A. de C. V., Mexico City (1957)
- Industrias Ocelco de México, S. A., Monterrey (1959)
- ITT Industrial, S. A. de C. V., Tlalnepantla (1949)
- Materiales de Telecomunicación, S. A., Toluca (1962)
- McClellan, S. A., Mexico City (1930)
- Standard Eléctrica de México, S. A., Mexico City (1953)

Panama

ITT Standard Electric of Panama, S. A., Panama City (1963)

Puerto Rico

ITT Caribbean Manufacturing, Inc., Rio Piedras (1962)

ITT Caribbean Sales and Service, Inc., Rio Piedras (1961)

United States

Federal Electric Corporation, Paramus, N. J. (1945)
- Intelex Systems Incorporated, Paramus, N. J. (1947)
- International Standard Engineering, Inc., Paramus, N. J. (1958)
- ITT Technical Services Inc., Paramus, N. J. (1958)

International Standard Electric Corporation, New York, N. Y. (1918)

International Telephone and Telegraph Corporation, Sud America, New York, N. Y. (1929)

ITT Abrasive Products Company, Tiffin, Ohio and Detroit, Mich. (1889)

ITT Arkansas Division, Camden, Ark. (1962)

ITT Cannon Electric (division), Los Angeles, Calif. (1915)

ITT Controls and Instruments Division, Glendale, Calif. (1966)
- Barton Instruments, Monterey Park, Calif. (1925)
  - ITT Snyder, Houston, Tex. (1948)
- General Controls, Glensdale, Calif. and Des Plaines, Ill. (1930)
- Hammel-Dahl, Warwick, R. I. (1940)
- Henze Valve Service, Hoboken, N. J. (1939)

ITT Data Services (division), Paramus, N. J. (1965)

ITT Electron Tube Division, Easton, Pa., and Roanoke, Va. (1962)

ITT Electro-Physics Laboratories Inc., Hyattsville, Md. (1966)

ITT Environmental Products Division, Philadelphia, Pa. (1966)
- Nesbitt, Philadelphia, Pa. (1917)
  - Hayes, Torrance, Calif. (1941)
- Reznor, Mercer, Pa. and Columbus, Ohio (1888)
- Wakefield Lighting, Vermilion and Cleveland, Ohio (1882)

ITT Export Corporation, New York, N. Y. (1962)

ITT Farnsworth Research Corporation, Fort Wayne, Ind. (1947)

ITT Federal Laboratories (division), Nutley, N. J.; San Fernando, Calif.; Fort Wayne, Ind. (1960; pred. co. 1909)

ITT Federal Support Services, Inc., Richland, Wash. (1965)

ITT Fluid Handling Division, Morton Grove, Ill. (1966)
- Bell & Gossett Hydronics, Morton Grove, Ill. (1916)
  - ITT Jabsco Inc., Costa Mesa, Calif. (1941)
- Marlow, Midland Park, N. J. and Longview, Tex. (1924)
- Stover, Freeport, Ill. (1907)

ITT Gilfillan Inc., Los Angeles, Calif. (1912)

ITT Illumination Inc., Lynn, Mass. (1967)
- Champion Lamp, Lynn, Mass. (1900)
- Amplex/Lustra, Carle Place, N. Y. (1934)

ITT Industrial Laboratories Division, Fort Wayne, Ind. (1962)

ITT Industrial Products Division, San Fernando, Calif. (1957)

ITT Industries, Inc., New York, N. Y. (1963)

ITT Jennings (division), San Jose, Calif. (1942)

ITT Mackay Marine (division), Clark, N. J. (1927)

ITT Microwave Inc., Mountain View, Calif. (1964)

ITT Semiconductors (division), West Palm Beach, Fla.; Lawrence, Mass.; Palo Alto, Calif. (1962)

ITT Telecommunications (division), New York, N. Y.; Corinth, Miss.; Milan, Tenn.; Raleigh, N. C. (1952)

ITT Terryphone Corporation, Harrisburg, Pa. (1946)

ITT Wire and Cable Division, Pawtucket, R. I. (1964)
- Royal: Pawtucket and Woonsocket, R. I. (1921)
- Surprenant: Clinton, Mass. (1946)

U. S. Telephone and Telegraph Corporation, New York, N. Y. (1965)

TELEPHONE OPERATIONS

Puerto Rico

Puerto Rico Telephone Company, San Juan (1914)

Virgin Islands

Virgin Islands Telephone Corporation, Charlotte Amalie (1959)

SOUTH AMERICA

MANUFACTURING—SALES —SERVICE

Argentina

Compañía Standard Electric Argentina, S. A. I. C., Buenos Aires (1919)

ITT Latin America Inc. (Area Headquarters), Buenos Aires (1967)

Brazil

Standard Eléctrica, S. A., Rio de Janeiro (1937)
- Eletrônica Industrial S. A., São Paulo (1960)

Chile

Compañía Standard Electric, S. A. C., Santiago (1942)

Colombia

ITT Standard Electric de Colombia, S. A., Bogotá (1963)

Ecuador

International Standard Electric of New York Limited (branch), Quito (1962)

El Salvador

International Standard Electric of New York Limited (branch), San Salvador (1962)

Surinam

ITT Standard Electric Surinam N.V., Paramaribo (1965)

Venezuela

Standard Telecommunications C. A., Caracas (1957)

TELEPHONE OPERATIONS

Chile

Compañía de Teléfonos de Chile, Santiago (1930)

Peru

Compañía Peruana de Teléfonos Limitada, Lima (1920)

EUROPE

MANUFACTURING—SALES —SERVICE

Austria

Standard Telephon und Telegraphen Aktiengesellschaft, Czeija, Nissl & Co., Vienna (1905)

Belgium

Bell Telephone Manufacturing Company, Antwerp (1882)
ITT Europe, Inc. (Area Headquarters), Brussels (1960)
ITT Standard S. A. (branch), Brussels (1961)

Denmark

Standard Electric Aktieselskab, Copenhagen (1931)

Finland

Standard Electric Puhelinteollisuus Oy, Helsinki (1940)

France

Cannon Electric France S. A., Toulouse and Paris (1962)
Centre Français de Recherche Opérationnelle (CFRO), Paris (1954)
Claude, Paz et Visseaux, Paris (1930)
Compagnie Générale de Constructions Téléphoniques, Paris (1892)
Compagnie Générale de Métrologie, Annecy (1942)
Laboratoire Central de Télécommunications, Paris (1945)
Le Matériel Technique Industriel, Paris (1940)
Le Matériel Téléphonique, Paris (1889)
Océanic-Radio, Paris and Chartres (1946)
Société des Produits Industriels ITT, Paris (1964)
Société Industrielle de Composants pour l'Electronique, Levallois-Perret (1963)

Germany

Deutsche ITT Industries GmbH, Freiburg (1952)
Dräger GC Regelungstechnik GmbH, Frankfurt (1958)
Intermetall GmbH, Freiburg (1952)
Standard Elektrik Lorenz Aktiengesellschaft, Stuttgart (1879)
Graetz Kommanditgesellschaft, Altena (1947), and other subsidiaries

Greece

ITT Hellas A. E., Athens (1965)

Italy

Fabbrica Apparecchiature per Comunicazioni Elettriche Standard S.p.A., Milan (1909)
Società Impianti Elettrici Telefonici Telegrafici et Costruzioni Edili S.p.A., Florence (1931)

Netherlands

Internationale Gas Apparaten N.V., Utrecht (1940)
Nederlandsche Standard Electric Maatschappij N.V., The Hague (1940)

Norway

Standard Telefon og Kabelfabrik A/S, Oslo (1915)

Portugal

Standard Eléctrica, S. A. R. L., Lisbon (1932)

Spain

Compañía Internacional de Telecomunicación y Electrónica, S. A., Madrid (1961)
Compañía Radio Aérea Marítima Española, S. A., Madrid (1931)
Standard Eléctrica, S. A., Madrid (1926)

Sweden

ITT Norden AB, Solna (1965)
Standard Radio & Telefon AB, Barkarby (1938)

Switzerland

Intel S. A., Basle (1961)
ITT Standard S. A., Basle (1964) (Branches in several countries)
Standard Téléphone et Radio S. A., Zurich (1935)
Müller-Barbieri AG, Wettswil (1959)
Steiner S. A., Berne (1927)

United Kingdom

Cannon Electric (Great Britain) Ltd., Basingstoke (1952)
Creed and Company Limited, Brighton (1912)
ITT Industries Limited, London (1964)
Maclaren Controls Limited, Glasgow (1844), and other subsidiaries
Standard Telephones and Cables Limited, London (1883)
Standard Telecommunication Laboratories Limited, London (1945), and other subsidiaries

AFRICA AND THE MIDDLE EAST

MANUFACTURING—SALES —SERVICE—

ITT Africa and the Middle East

(a division of ITT Europe, Inc.)
Area Headquarters: London (1966)

Algeria

Société Algérienne de Constructions Téléphoniques, Algiers (1947)

Iran

Standard Electric Iran AG, Tehran (1955)

Nigeria

ITT Nigeria Limited, Lagos (1957)

Republic of South Africa

Standard Telephones and Cables (South Africa) (Proprietary) Limited, Boksburg East (1956)
Supersonic Africa (Pty) Limited, Boksburg (1951)

Rhodesia

Supersonic Radio Mfg. Co. (Pvt) Limited, Bulawayo (1950)

Tunisia

ITT Hotel Corporation of Tunisia, Tunis (1967)

Turkey

Standard Elektrik ve Telekomünikasyon Limited Sirketi, Ankara (1956)

Zambia

ITT (Zambia) Limited, Ndola
Supersonic Radio Zambia Limited, Livingstone (1965)

Regional offices of ITT Africa and the Middle East:

Luanda, Angola; Kinshasa (Leopoldville), Congo; Nairobi, Kenya; Beirut, Lebanon; Dakar, Senegal; Tunis, Tunisia.

FAR EAST AND PACIFIC

MANUFACTURING—SALES—SERVICE—OPERATIONS

Australia

Cannon Electric (Australia) Pty. Limited (50% interest), Melbourne (1955)

ITT Oceania Pty. Limited, Sydney (1966)

Standard Telephones and Cables Pty. Limited, Sydney (1912)

ITT Australia Pty. Limited, Brisbane and other cities (1930)

Hong Kong

ITT Far East and Pacific, Inc. (Area Headquarters), Hong Kong (1961)

ITT Far East Ltd., Hong Kong (1961)

Transelectronics, Limited, Hong Kong (1965)

India

ITT Far East and Pacific, Inc. (branch), New Delhi (1965)

Japan

ITT Far East and Pacific, Inc. (branch), Tokyo (1961)

New Zealand

Standard Telephones and Cables Pty. Limited (branch), Upper Hutt, Wellington (1914)

Philippines

Globe-Mackay Cable and Radio Corporation, Manila (unit of ICO Group, next column) (1935)

ITT Philippines, Incorporated, Makati, Rizal (1960)

Philippine Press Wireless, Inc., Manila (unit of ICO Group, next column) (1937)

BUSINESS AND CONSUMER SERVICES

Abbey Life Assurance Company Ltd. (50% interest), London (1961)

Alexander Hamilton Life Insurance Company, Denver, Colo. (1963)

Hamilton Management Corporation, Denver, Colo. (1931)

Intel Finance S. A., Lausanne (1965)

Internationale Levensverzekering Mij N. V. (50% interest), Amsterdam (1966)

ISE Finance Holdings S. A., Luxembourg (1966)

ITT Avis, Inc., Garden City, N. Y. (1956)

ITT Consumer Services Corporation, New York, N. Y. (1966)

APCOA, Cleveland, Ohio (1954)

ITT Aetna Finance Company, Clayton, Mo. (1918)

ITT Financial Services Inc., New York, N. Y. (1964)

Great International Life Insurance Company (50% interest), Atlanta, Ga. (1964)

International Telephone and Telegraph Credit Corporation, New York, N. Y. (1961)

Kellogg Credit Corporation, New York, N. Y. (1953)

ITT Life Insurance Company, Clayton, Mo. (1955)

Howard W. Sams & Co., Inc., Indianapolis, Ind. (1946)

INTERNATIONAL COMMUNICATIONS OPERATIONS

American Cable & Radio Corporation, New York (1939)

All America Cables and Radio, Inc. (1878)

Commercial Cable Company, The (1883)

Globe-Mackay Cable and Radio Corporation (1935)

ITT Central American Cables and Radio, Inc. (1963)

ITT Cable and Radio, Inc.—Puerto Rico (1922)

ITT Communications, Inc.—Virgin Islands (1963)

ITT World Communications Inc. (1926)

Press Wireless, Inc. (1929)

Philippine Press Wireless, Inc. (1937)

Press Wireless Uruguaya (1942)

Teleradio Brasileira Limitada (1938)

Companhia Rádio Internacional do Brasil, Rio de Janeiro (1930)

ITT Comunicaciones Mundiales S. A., Buenos Aires (1928)

ITT Comunicaciones Mundiales S. A., Santiago (1928)

Radio Corporation of Cuba, Havana (1922)

NOTE: International telegraph offices are operated in the following countries: Argentina, Bolivia, Brazil, Canada, Canal Zone, Chile, Dominican Republic, Ecuador, Haiti, Netherlands Antilles, Nicaragua, Panama, Peru, Philippines, United Kingdom, United States (including Puerto Rico and the Virgin Islands), Uruguay, Venezuela.

INTERESTS (minority and other) AND ASSOCIATE LICENSEES

Australia

Austral Standard Cables Pty. Limited, Melbourne (1948)

France

Lignes Télégraphiques et Téléphoniques, Paris (1920)

Italy

Società Italiana Reti Telefoniche Interurbane, Milan (1921)

Japan

Nippon Electric Company, Limited, Tokyo (1899)

Sumitomo Electric Industries, Limited, Osaka (1920)

Spain

Marconi Española, S. A., Madrid (1935)

Figures in parentheses refer to founding date of unit or predecessor.

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