No. 200

The Institution of Post Office Electrical Engineers.

Trends in the Design of Line Transmission Equipment

by

R. J. HALSEY, B.Sc. (Eng.), A.C.G.I., D.I.C., M.I.E.E.

A Paper read before the Glasgow Centre of the Institution on the 16th November, 1949, and at other Centres during the Session

No. 200

The Institution of Post Office Electrical Engineers

Trends in the Design of Line Transmission Equipment

by

R. J. HALSEY, B.Sc. (Eng.), A.C.G.I., D.I.C., M.I.E.E.

A Paper read before the Glasgow Centre of the Institution on the 16th November, 1949, and at other Centres during the Session

CONTENTS

Trends in the Design of Line Transmission Equipment

I. INTRODUCTION

Line transmission equipment, as we now understand it, had its beginnings in the Post Office system during the first World War when some experimental speech amplifiers were fitted in underground cables ; most stages of the subsequent development can still be seen in our repeater stations. Repeaters of the 1920s, with their convenient but trouble-ridden jack fields, still exist at places such as Taplow and Fenny Stratford, a typical repeater occupying 10½ in. of mounting space on both sides of a bay (Fig. 1).

In America, 1 + 1 and 1 + 3 circuit carrier telephone systems were developed for open-wire lines and came into extensive use abroad in the late twenties. In this country such systems never became an important part of the network, which was rapidly going underground ; only in the more remote parts, e.g., the Scottish Highlands, did they find useful application.

The period up to 1936 was characterized mainly by substantial reductions in bulk and cost ; notable was the " toll " amplifier, a simple, inexpensive unit for secondary cable routes, usually fitted at exchanges. Improving transmission standards led to a changeover from 2-wire to 4-wire working on trunk routes ; 1 + 1 circuit, 4-wire carrier systems were also used on loaded cables but carrier development was restricted by the quality of the amplifiers then available.

Telephone and telegraph services became integrated by the introduction, in 1932, of 18-channel carrier telegraph systems capable of operating over normal speech channels ; the carrier frequencies (C.C.I.T.) are odd multiples of 60 c/s, 420—2460 c/s. This system, originally introduced for audio circuits, is also used on carrier circuits and the very limited additional frequency shift which it will accommodate usually determines the necessary stability of the telephone carrier frequencies.

In 1934 the principles and advantages of negative feedback were recognized and the consequent stabilization of amplifiers encouraged development of the 12-circuit and coaxial systems which now form the main trunk network. By 1939 it was decided to extend the use of multi-pair cables from 12 to 24 channels per pair, but this policy was delayed for the expansion of the coaxial cable network ; only now is it coming to full fruition. The relative economy of 24-circuit and coaxial systems has now been resolved in favour of the latter and the era of 24-circuit system provision in this country is now ending.

The wide use of coaxial and, indeed, of 12- and 24-circuit systems, has been facilitated by the introduction of high-frequency distribution frames (H.F.R.D.F., 12-60 kc/s or 12-108 kc/s ; G.D.F., 60-108 kc/s) and by the use of through-group filters which enable 12-channel groups to be isolated and switched at the G.D.F. To-day, the need for switching of larger units (super-groups of 60 channels in the range 312-552 kc/s) is urgent, but the technical solution of the problem is proving troublesome and costly.

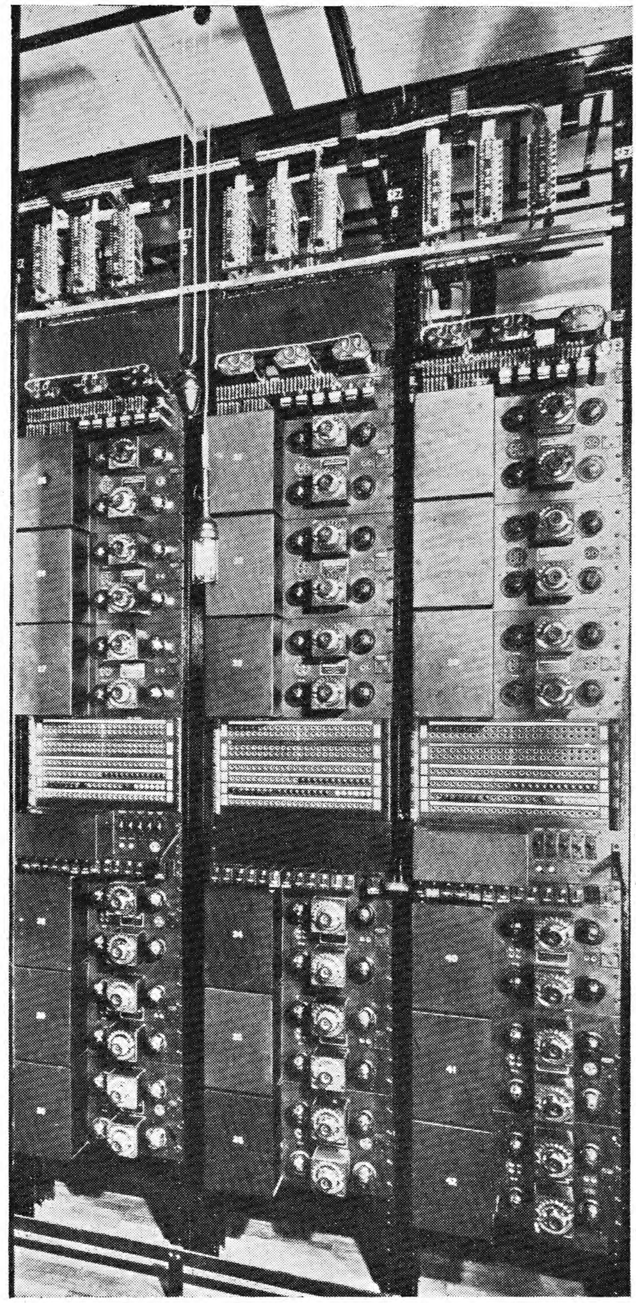


FIG. 1.—4-WIRE REPEATERS OF THE 1925-1930 ERA.

2. RECOMMENDATIONS OF THE C.C.I.F. AND C.C.I.T.*

The recommended characteristics and performance of international circuits are defined by the C.C.I.F. and C.C.I.T. in their respective spheres. While these recommendations are not intended to apply to internal circuits they do, in practice, set standards for such circuits ; no administration can treat its national and international circuits entirely independently.

2.1. Telephone Systems

Since the war, the C.C.I.F. has endeavoured to rationalize planning to a much greater extent than previously. In addition to audio and low-frequency carrier systems it has now standardized multi-channel systems[1]† based on two alternative 12-channel primary groups (12-60 kc/s, channels erect, and 60-108 kc/s, channels inverted).

1. 24-circuit systems on multi-pair cables, transmitted in the range 12-108 kc/s (some countries use only 12 channels per pair, others up to 48).
2. 960-circuit systems on coaxial cables, transmitted as 16 super-groups of 60 channels in the range 60-4028 kc/s (see Table). A system of 10 super-groups in the range 60-2540 kc/s is also recognized.

Unit.	Frequency Range kc/s.	Channel Sidebands.
Primary Group A	12—60	Erect
Primary Group B	60—108	Inverted
Primary Super-Group†	312—552	Erect
Super-Group 1	60—300	Inverted
Super-Group 2	312—552	Erect
Super-Group 3	564—804	Inverted
Super-Group 4	240 kc/s units separated by 8 kc/s gaps	Inverted
,,		
,,		
,,		
Super-Group 16		

† Super-group modulation is not specifically required by the C.C.I.F.

3. 12-circuit grouped systems on open-wire lines ; agreement on frequency bands has not been possible but maximum frequencies extend to about 160 kc/s.

The first two types are specified in some detail ; for coaxial systems the preferred arrangement is ⅜ in. coaxial pairs with repeaters at 10 km (6.2 miles) spacing.

Supervisory and testing frequencies are proposed as follows :—

1. Gain regulation, 60 or 308 kc/s and 2604 or 4092 kc/s for 10 or 16 super-groups respectively ; other frequencies for this purpose will be located between super-groups.
2. Frequency control or comparison, 60 or 308 kc/s or another frequency to be agreed (possibly 1800 kc/s).
3. Pilot-fail alarm, 60 or 308 kc/s.
4. Reference frequencies, 36 or 84 kc/s for groups, 412 kc/s for super-groups ; these will be used for routine transmission measurements and, possibly, for automatic gain regulation.

Carrier frequencies are to have a stability better than 1 in 10^7.

Until recently, there has been no definition of the length or complexity of circuits which should conform to C.C.I.F. recommendations and, from the design and planning aspect, a new decision in this connection is important. In this, the C.C.I.F. recognizes a " nominal maximum circuit " as " a hypothetical circuit having a defined length and a defined amount of terminal and intermediate equipment, these quantities being reasonably large but not extreme." For a circuit on coaxial cable, the length is 2500 km and includes, in each direction, three pairs of channel-translating equipments, six pairs of group-translating equipments and nine pairs of super-group-translating equipments. It thus becomes possible to allocate agreed maximum noise or distortion between the various items in the circuit ; a circuit longer than the "nominal maximum" would be allowed a correspondingly lower performance.

Signalling. The C.C.I.F. is now sponsoring tests with two types of signalling systems, a 2 V.F. system using 2040 and 2400 c/s and a single-frequency system using 2280 c/s ; no decision has yet been reached. For the national network a single-frequency system is the long-term target.

2.2. Music Channels

Music channels will be provided as an alternative to three speech channels at primary-group frequencies to be agreed ; the British Post Office favours 84-96 kc/s, which avoids spurious resonances in through-group filters (these cause narrow stop bands at carrier frequencies) and also supervisory and testing frequencies.

2.3. Telegraphs

Telegraph channels will be provided as at present but with a speech band 300-3400 c/s now standardized, the number per system will be increased to 24.

2.4. Television

In recommending a coaxial cable system for telephony, the C.C.I.F. had in mind also the requirements of television (3 Mc/s band) and the 60-4028 kc/s band is suitable for this purpose. Details of the modulation have not been specified.

* (C.C.I.F.) Comité Consultatif International Téléphonique.
(C.C.I.T.) Comité Consultatif International Télégraphique.

† Numerical references are to the Bibliography at the end of the Paper.

3. TYPES OF CONSTRUCTION

Panel mounted equipment occupying only one side of a bay has now been general for many years, but the mechanical construction of the units and also of the bays themselves will almost certainly undergo radical alteration in the near future. The present rolled-steel sections are unnecessarily heavy and pressed-steel or light alloy constructions have many advantages ; serious consideration will also be given to height reduction. Under present conditions equipment for home and for export should differ as little as possible and as it is frequently impossible to accommodate 10 ft. 6 in. bays abroad, a height of 9 ft. is favoured. In America 11 ft. 6 in. is standard.

Current French construction is shown in Figs. **2** and **3**. Bay wiring is terminated on sockets on the pressed-steel framework ; panel wiring is similarly terminated and connections are by bridging U-links. Such a construction, which enables panels to be removed quickly, has two advantages ; it facilitates replacement of faulty units and simplifies handling in awkward locations. The individual boxes on the panels are developed from the earlier and less elegant German " Baukasten " construction.

A more advanced type of construction—New Equipment Practice (N.E.P.)—has been developed in this country[2] and is at present under test by the Post Office. It combines a pressed-steel bay with a Meccano-like panel assembly (Fig. **4**) giving considerable flexibility with standardized piece parts. The 9 ft. bay units are single-sided and can be mounted back-to-back if desired. Typical bays, mounting two groups of channel equipment per side, are shown in Fig. **5** with Carrier Systems No. 7 in the background ; removal of a channel panel is illustrated in Fig. **6**. Connection with the bay cabling is via flat-bladed U-links with soldering tags provided for use after the equipment has been lined up. N.E.P. represents the first serious attempt to plan transmission equipment for mass production and the necessary press tools represent a large capital outlay, justified only by large-scale production.

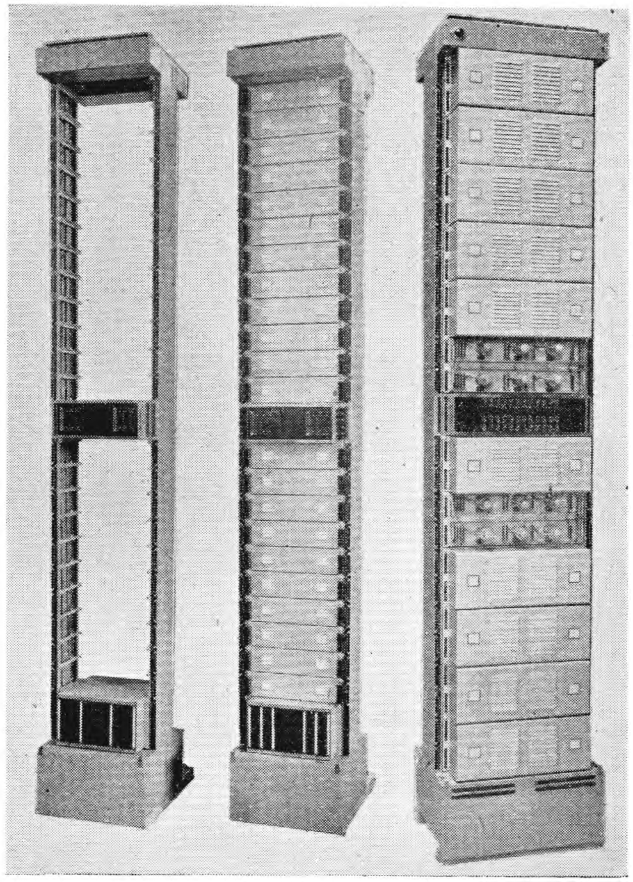


FIG. 2.—TRANSFORMER BAY. 36-CHANNEL REPEATERS. FRENCH EQUIPMENT PRACTICE, 1944.

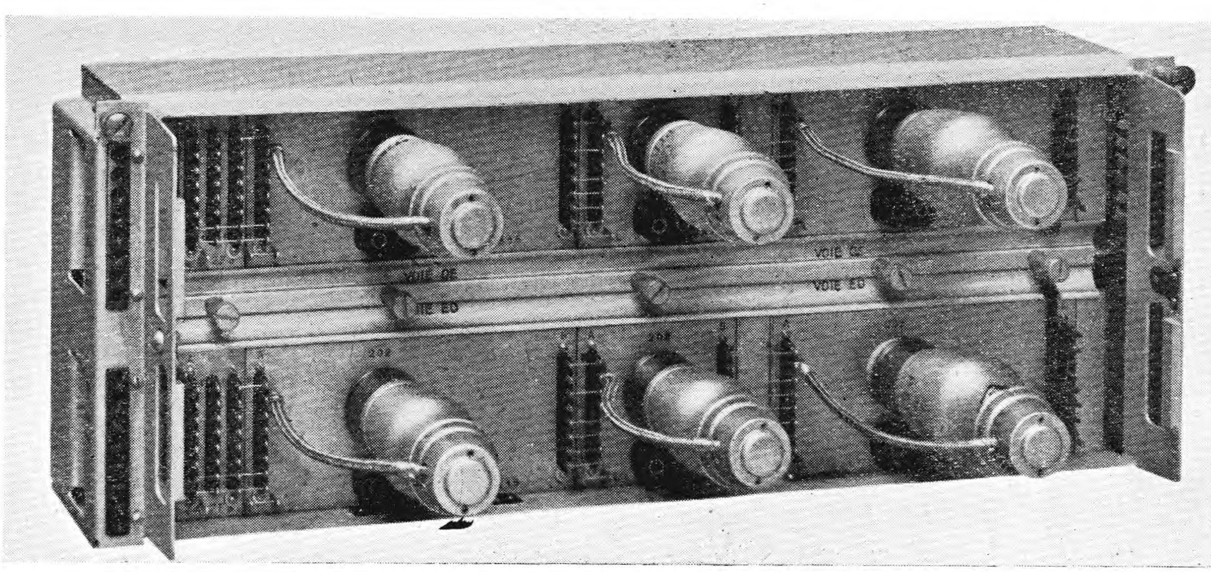


FIG. 3.—FRENCH 36-CHANNEL REPEATER, 1944 DESIGN.

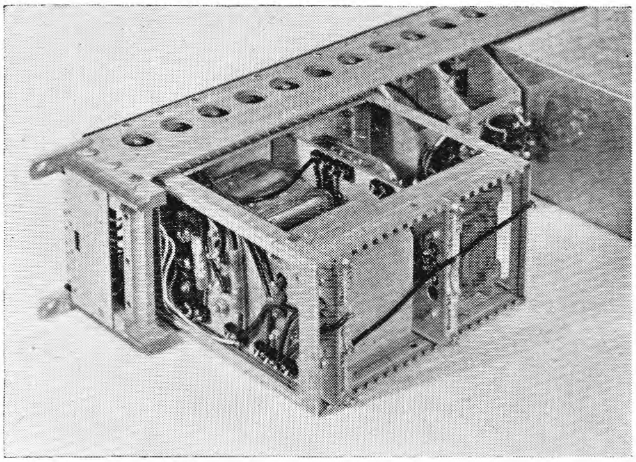


FIG. 4.—N.E.P.—AUDIO-FREQUENCY LINE AMPLIFIER. (BACK OF PANEL. SEALED COVER REMOVED.)

3.1. Mounting of Components

In early equipment, components were individually potted, the first departure from this practice being the inclusion of small capacitors and resistors in the transformer pots (e.g., Unit Amplifier No. 32). With the use of higher frequencies this practice became undesirable owing to the importance of parasitic reactances and, for most types of carrier line amplifiers it became usual to mount components on open assemblies or, more frequently, direct in the wiring, logical location being of great importance. For high-frequency amplifiers developed for maximum utilization of submarine cables, components are mounted and screened to minimize pick-up both direct and via earth circuits.

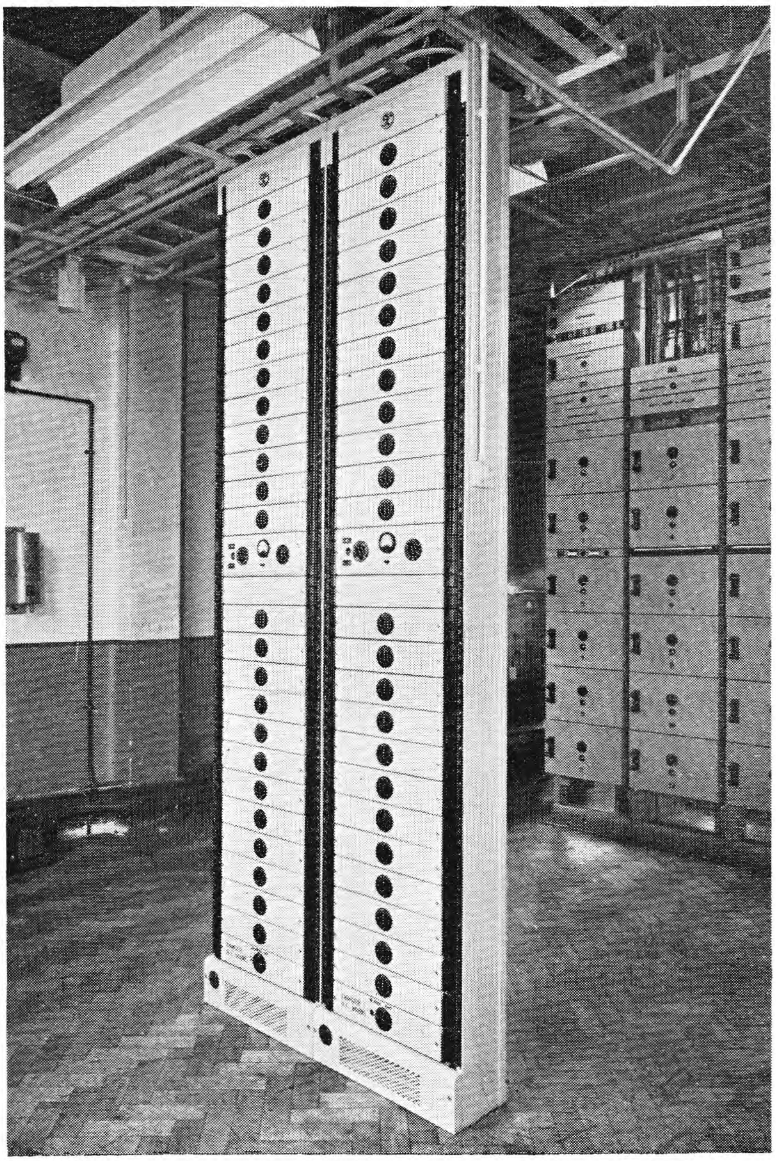


FIG. 5.—N.E.P.—12-CIRCUIT TERMINAL EQUIPMENT.

This often necessitates double-screening to preserve a " coaxial " structure* and to take proper account of earth currents (Fig. **7**).

For filters and other passive networks, individually potted components have been superseded by assemblies in single cans, sub-divided where necessary and often hermetically sealed (Figs. **8** and **9**). Primarily developed for tropical conditions, this technique is very useful in unattended stations. Silvered-ceramic and glass-metal seals are common but neither is entirely satisfactory. In America, neoprene (synthetic rubber) gaskets and moulded seals are often used ; in this country, fused alumina seals using " sparking plug " technique are probably the best available.

These new mounting techniques have greatly reduced the accessibility of components and this, in conjunction with complicated circuitry and the subtle effects of parasitic reactances, has made servicing *in situ* very difficult. It is now accepted that modern equipment cannot be serviced in the same casual manner as was possible with more elementary systems and so the main requirement from the point of view of the attendant is that units shall be readily replaceable. This enables the designer to adopt designs not requiring to be wired and serviced from one direction.

Anode alarm relays, impracticable in many modern circuits, are tending to disappear. A scheme giving an equivalent facility—alarm on failure of cathode bias voltage—has been used but has not been generally adopted.

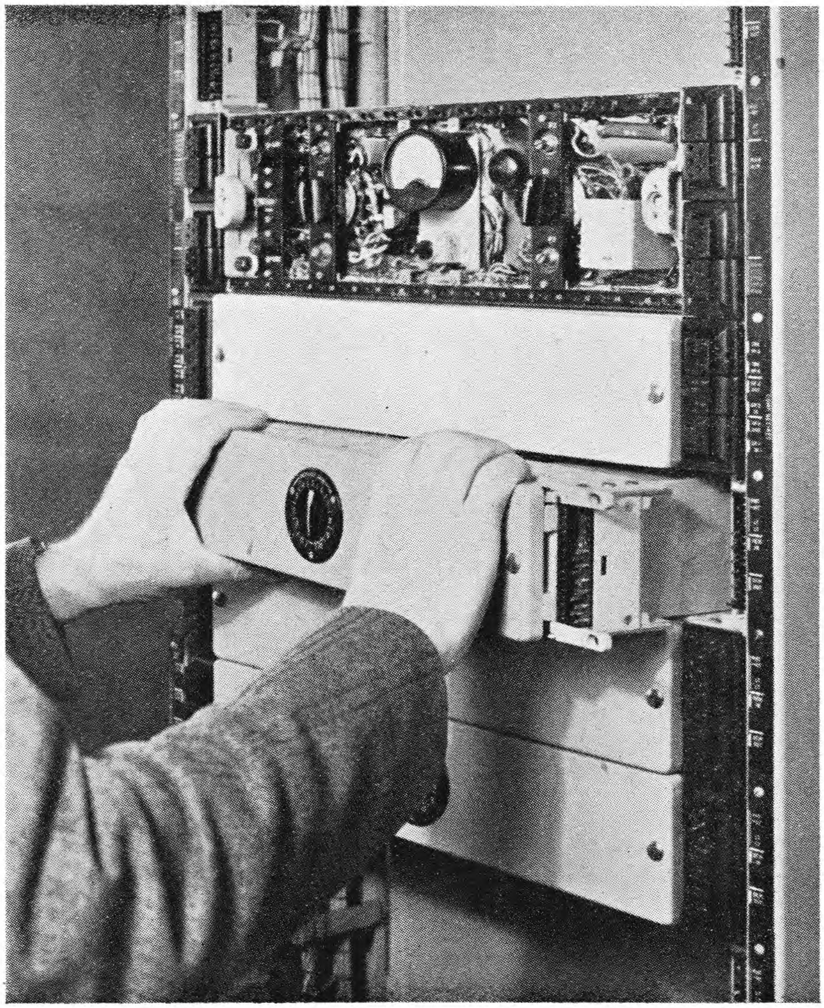


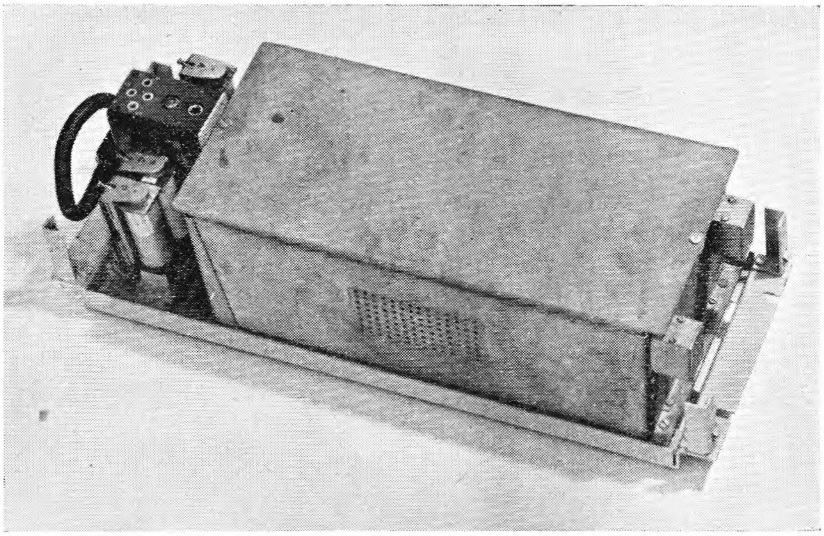
FIG. 6.—N.E.P.—REMOVING A CHANNEL PANEL.

3.2. Miniaturization

Equipment has been steadily reduced in size over a period of many years, but Service requirements during and since the war have given a great impetus to " miniaturization " techniques.

The accommodation problem faced by the Post Office in the next decade is a serious one and probably,

* It is convenient to use this term to describe a structure in which the components are completely enclosed by a screen which carries the return current on its inner surface.



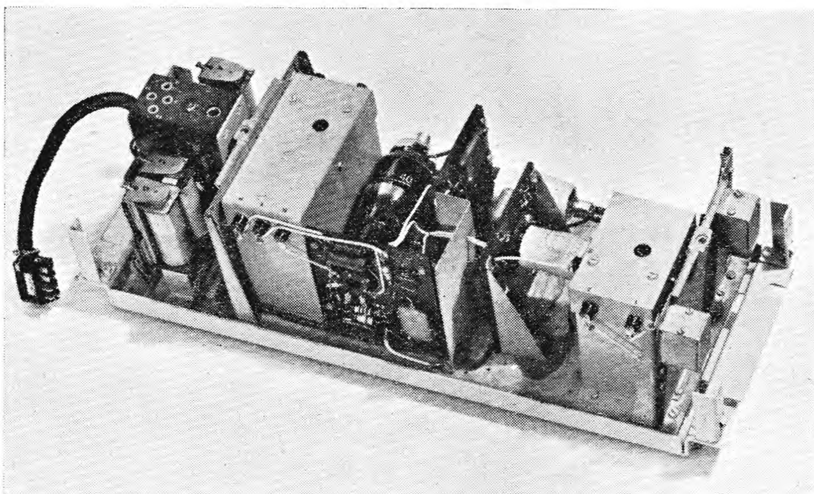


Fig. 7.—Double-screened Amplifier for Submarine Cable System.

in itself, justifies miniaturization. Cost of equipment has, so far, generally tended to fall as size is reduced but the economical optimum has not yet been properly determined.

Arguments against miniaturization are that:—

1. Performance standards and reliability may be reduced ;
2. maintenance is more difficult ;
3. accommodation charges are only a small fraction of the total ;
4. local heating and space heating problems become more difficult and, if special air-conditioning plant is necessitated, this may more than offset direct advantages.

The Post Office has now set as a standard for new channel equipment four groups per bay, i.e., twice the concentration of C.S. No. 8 and four times that of C.S. No. 7. A further size reduction by one half—two complete channels per 3½ in. panel—has been achieved experimentally.

3.3. Printed Circuits*

The technique of circuit printing[3] is making considerable progress. Wiring and certain components—resistors, H.F. inductors and small capacitors—can now be printed, but the tolerances permissible in line equipment are such that only printed wiring can, as yet, be seriously considered. Techniques are very varied. In one attractive system a sheet of copper foil is bonded to a plastic base, either rigid or flexible ; areas to be retained are printed with an acid-resistant ink, the remainder being subsequently etched away. Valve sockets, components, etc., can be soldered to the " printed " wiring which is strongly adherent to the plastic base.

* Many of the processes involved are not printing in its proper sense, but the term is used in a generic sense to cover a wide range of techniques.

The advantages of printing techniques are low cost in quantity production, elimination of wiring errors and a high degree of reproducability which is valuable where wiring reactances are important. On the other hand, stray capacitances may be greater than with open wiring.

A different technique has been used experimentally in a miniature audio-frequency line amplifier[4] produced experimentally by the Post Office (Fig. **10**). In this the wiring is stamped out complete with connecting tags for components and external wiring.

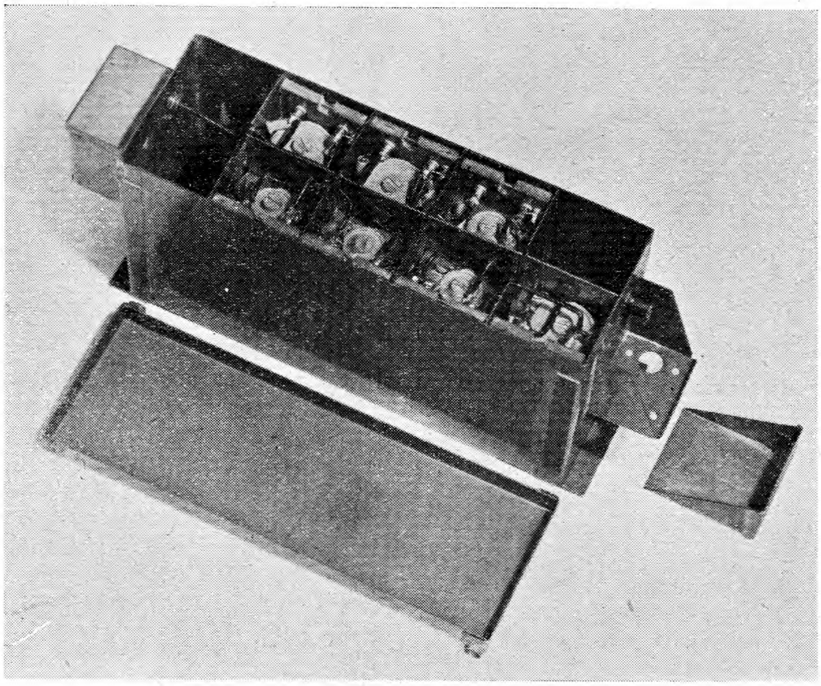


FIG. 8.—FILTER ASSEMBLY FOR SUBMARINE CABLE SYSTEM.

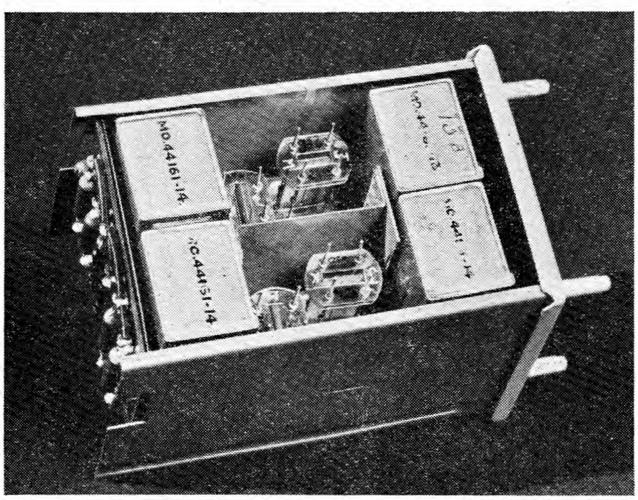


FIG. 9.—CRYSTAL FILTER (N.E.P.)—SEALED COVER REMOVED.

3.4. The Space Heating Problem

It is on the question of space heating that miniaturization really seems to turn. A study of existing installations has led to the conclusion that the temperature rise in repeater stations should not exceed 10—15°F and, accordingly, that the maximum power dissipated per 1000 cubic feet in an apparatus room having natural ventilation should not exceed 0.8—1.0 kW and that for greater values it will be necessary to employ forced ventilation or air-conditioning.

Air - conditioning probably cannot be justified economically, in which case the allowable dissipation is 150 watts per bay with the present spacing of 4 ft., corresponding to 1 kW / 1000 cubic ft. This is restrictive indeed, for a bay of new type channel equipment using only one valve per circuit dissipates 140 watts. It seems then that no space may be saved by further miniaturization.

This problem needs further attention because the limits imposed appear too restrictive; it is significant that in America much greater dissipations are tolerated despite higher ambient temperatures. In the field of electronic computors, with which telephony techniques may ultimately tend to merge, new American equipment accommodates up to 500 sub-miniature valves per cubic foot. Moulded plastic sub-assemblies are used and the temperature is given as 105—115°C !

The anomalous position is again illustrated by the miniature audio-frequency amplifier shown in Fig. **10**.

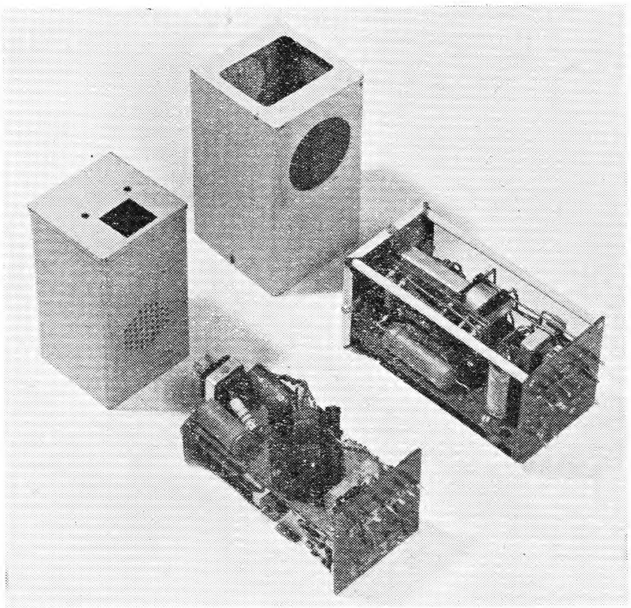


FIG. **10**.—MINIATURE AUDIO-FREQUENCY LINE AMPLIFIER.

Some 400 of these amplifiers (more if " printed ") will mount on a 10 ft. 6 in. bay, the dissipation being 1.5 kW. Even if diluted by line transformers and equalizers the dissipation with normal bay spacing exceeds the proposed limit by a factor of 4. Comparable amplifiers (600 units, 1.4 kW, per bay) have recently been introduced in America[5] (Fig. **11**) without special arrangements and, seemingly, without adverse comment. Local heating difficulties could be largely overcome with the Post Office design by associating line equalizers and line transformers with the amplifiers, thus reversing the practice, introduced with UA 32, of associating equalizers with the lines and transformers.

In future the tendency will be to use many more valves than at present and heating difficulties may become greatly accentuated. Ranges of components capable of withstanding temperatures up to 100°C. are becoming available, primarily for Service use.

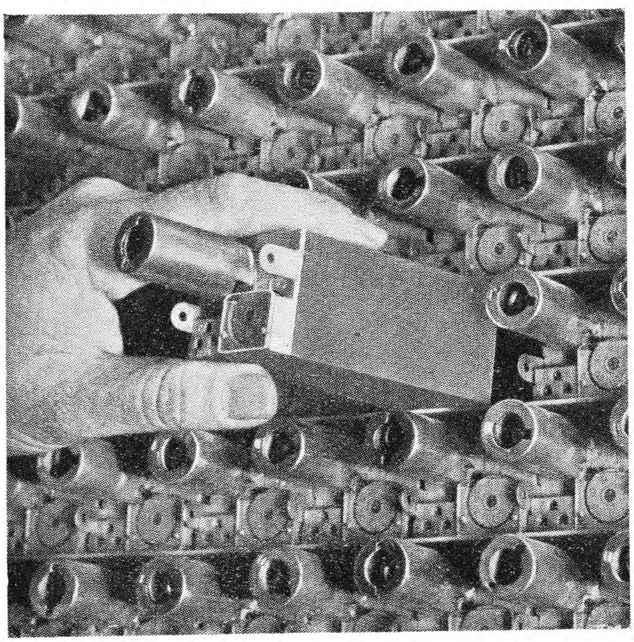


FIG. **11**.—MINIATURE AUDIO-FREQUENCY LINE AMPLIFIERS (B.T.L.).

4. NEW TYPES OF COMPONENTS

Much effort in component design has been directed at securing adequate performance under conditions encountered by Service equipment, and this has not always developed the characteristics desirable in civil communication equipment ; there has, however, been considerable progress.

4.1. Miniature Valves

Valves are now available in both miniature and sub-miniature ranges. The former includes a high performance series ; CV 138, for instance, is an indirectly-heated high-slope pentode having a higher figure-of-merit than any standard-sized valve. The B7G base is not sufficiently reliable for transmission equipment and solder-in holders have therefore been designed (Fig. **12**). The sub-miniature class originally contained only valves of comparatively low performance, but a new type, having even a better figure-of-merit than CV 138, is now available experimentally. Even smaller " grain-of-rice " valves have been used in America.

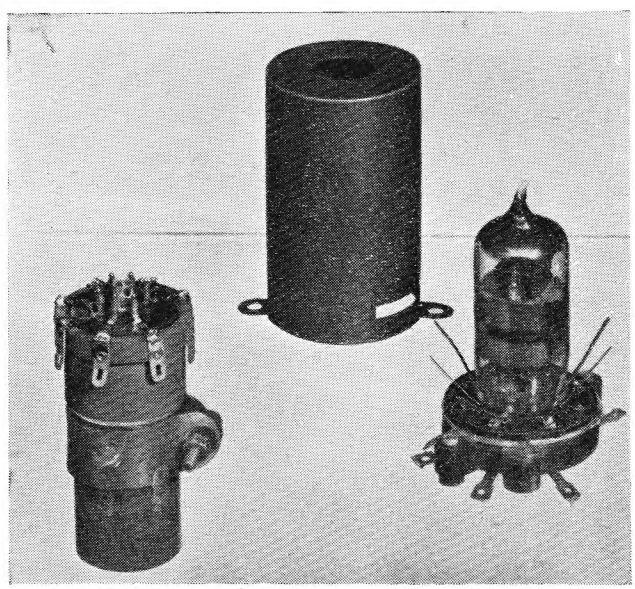


FIG. **12**.—SOLDER-IN HOLDERS FOR B 7 G-BASED VALVES.

4.2. Crystal Triodes

Much publicity has been given to crystal triodes[6] (transistors) but, although these are clearly of great potential value for certain types of amplifiers, no immediate application is envisaged in line transmission. Shortcomings of available units are:—

1. Low gain (10-15 db.) ; where requirements necessitate tandem stages the gain per unit of power consumed compares unfavourably with thermionic valves.
2. High internal noise, about 60 db. above valve noise at 1000 c/s and inversely dependent on frequency to the extent of about 10 db. per decade.
3. With the most convenient electrode connections (corresponding to a grounded grid triode) the input impedance is low and the output impedance high ; this usually necessitates coupling transformers.
4. Limitation of operating frequency to a few Mc/s due to transit time.
5. Low power handling capacity (about 24 mW).*

Ingenious constructional methods are being developed to secure the necessary electrode spacing of about 0.002″ (Fig. **13**) and it is probable that robust units will soon be available in quantity. Adequate control of the quality of the germanium is difficult as certain impurities are significant in concentrations of 1 in 10^6.

4.3. Rectifiers

The elements used in balanced modulators have always, so far, been copper oxide rectifiers but, by modern standards, stability of both transmission loss and carrier leak leaves much to be desired. For high-frequency modulators where capacitance is important, crystal diodes provide a uniform response up to several Mc/s and the use of germanium diodes for group and super-group modulators is now almost certain. Development of germanium diodes with suitable characteristics for channel modulators, e.g., low forward resistance at low carrier voltage, is proceeding, and the prospect here too is encouraging.

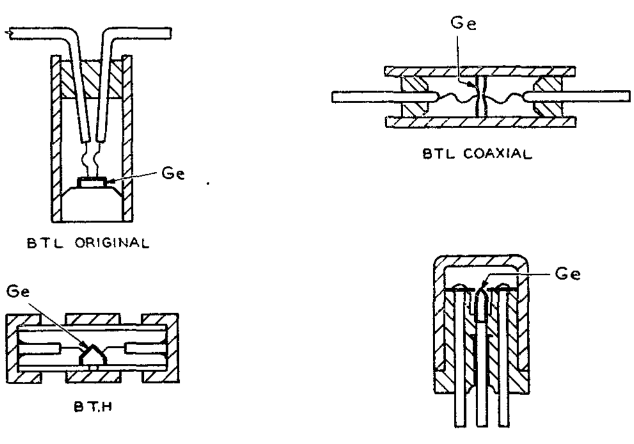


FIG. 13.—CRYSTAL TRIODES.

* Outputs up to 600 mW have recently been reported.

4.4. Transformer Cores

Improvements have been made in ferromagnetic cores for all purposes. A new alloy, Supermalloy, developed in America, has extremely high initial permeability—about 100,000 against about 20,000 for Permalloy C or Mumetal—and this will facilitate design of transformers of greater band-width ratios. Nickel - iron strip generally is now available in thicknesses down to about 0.0006 in. (in America, 0.00015 in.) ; thin Rhometal and Permalloy D strip are used for transformers in coaxial-line amplifiers. Methods of insulating the strip have been improved and greater uniformity of performance is now obtainable than hitherto ; the space factor of British cores using thin strip is, however, much less than that obtained in America with insulation applied by catephoresis.

To enable strip cores to be readily assembled in bobbins, i.e., without the use of a toroid winder, they are sometimes made with two straight limbs, cemented and cut transversely (C-type cores).

For wide-band transformers such as those required for coaxial-line amplifiers the superiority of thin strip is now being seriously challenged by ferrites, notably Ferroxcube III (Mn-Zn ferrite). This has a permeability of 800-2000, a resistivity of 10Ω—cm and cores are formed by moulding and sintering. At the present time the cores are more uniform than thin strip cores and, unless further improvements in the latter are forthcoming, they may well be superseded by ferrites.

4.5. Filter Inductor Cores

For precision inductors at lower frequencies, ferrites have outstandingly low losses ; for example, a coil of total volume 1.5 ins.,[3] using Ferroxcube III, has a Q-factor of 600-700 at 60 kc/s. The Curie point is about 120°C., but the temperature stability is usually adequate when air-gaps are used. Ferrites are usually fabricated as pot cores and, because of their high permeability, are self screening. For ring cores several grades of carbonyl iron are now available, including Carbonyl C, which will press to a permeability of 40 ; in nickel iron, permeabilities up to 125 are usual. Wedding-ring cores having an outside diameter of $\frac{13}{16}$ in. can now be wound satisfactorily and are of considerable value for miniaturized equipment.

4.6. Capacitors

For precision capacitors, silvered-mica plates have now generally replaced foil and mica ; they are, however, subject to scintillation effects, characterized by small irregular fluctuations in capacitance and slight non-linearity. Where linearity is very important (e.g., directional filters for submarine cable systems) foil must be used. Before the war, oriented polystyrene film (styroflex) was developed in Germany in thicknesses down to 0.0004 in. and was largely used for filter capacitors. Rolled, self-clamping capacitors of this type are now available here in small quantities ;

they have low losses (Q = 4000) at line transmission frequencies and can be supplied to $\pm$ 0.5% tolerance ; the temperature coefficient of capacitance is $-130/10^6/°C$. These capacitors should prove both smaller and cheaper than stacked mica. For temperature compensation of resonant circuits, ceramic capacitors with standard temperature-coefficients are available. These may be of permittivity about 14 with temperature coefficient $+40/10^6/°C$., or about 80 with temperature coefficient $-800/10^6/°C$., both being unaffected by applied voltage and having low power factors. Permittivities greater than 100* are associated with high power factor and large changes of capacitance with temperature and voltage. Synthetic mica has been made both in Germany and U.S.A., but is very uneconomical compared with the natural product.

For replacement of mica capacitors of lower precision the use of special glass is becoming important in America, where substitute materials are being thoroughly explored. Units are completely sealed in glass and, with permittivities approaching 10, the volume efficiency compares favourably with mica.

For non-precision uses metallized paper (usually evaporated zinc) is available and by an ingenious process it is now possible to form the two electrodes on the same side of a single coil of paper. By this means extremely small units can be made, suitable for voltages up to about 150.

The use of electrolytic capacitors in transmission equipment has usually been avoided owing to their unreliability ; there is now promise of considerable improvement in such capacitors. An interesting alternative development is of capacitors having very thin dielectric films of high permittivity ceramic (K = 2 – 3000) ; these may approach electrolytics in volume efficiency although the cost is likely to be high ; $50\mu F/in^3$ has been claimed with platinized electrodes.

4.7. Resistors

Progress in resistor design has been rather disappointing. Carbon resistors have been available for many years, as both rods and cracked films on ceramic. The former are cheaper and rather more robust and are available with rated dissipations down to 0.1 watts ; they are, however, unstable with time and unsuitable for precision circuits. Carbon-film resistors, which have a lower noise factor, are also available in similar ratings and, with the best types, stabilities considerably better than 1% can be maintained. Many attempts have been made to produce resistors as thin metallic films, but without conspicuous success. Such resistors have moderate positive temperature-coefficients for thicknesses well in excess of molecular dimensions, but reduction beyond a critical point causes large negative temperature-coefficients.

* High permittivities are analogous to high permeability in ferromagnetic materials, but the effect of "alloying" ferro-electric materials has not yet been properly explored.

4.8. Piezo-electric Resonators

During the war, consumption of quartz increased enormously and the supply position gave cause for concern. Resonators for channel filters do not represent an important fraction of the total demand but, being of large dimensions, they form a high-grade requirement. Both here and in America substitution of natural quartz has been approached by the development of:—

1. Synthetic quartz ; this has been successful but is unlikely to reach a commercial scale while natural supplies are available.
2. Water-soluble piezo-electric crystals ; of several useful materials the most promising is ethylene diamine tartrate.[8] (E.D.T.).

In this country, the need for replacing natural quartz in filter resonators has been brought about by its recognition as a strategic material, with H.F. oscillators requiring priority, and by the high dollar cost. The stability of water-soluble materials does not suggest any immediate possibility of replacing quartz in H.F. oscillators. In America, field trials of E.D.T. channel filters have been in progress for some time, but only the six lowest channels (the largest crystals) have been re-engineered. In this country valuable new cuts have been developed, some apparently superior to those used in America and field trials of complete sets of filters are in hand.

Being water-soluble, E.D.T. crystals must be sealed and glass envelopes have been employed initially. Later, means for mounting one or more crystals in sealed metal containers may be developed. Means for attaching wires direct to quartz plates at nodal points have been in use for some time ; a spot of silvering paste is applied to the crystal and reduced to metallic silver to which the wire is soldered in a hot air jet. This is unsuitable for E.D.T., which will not withstand temperatures in excess of 120°C., and new methods have been necessary. The usual method is to stick the flattened end of the wire to the crystal with a bakelite cement (e.g., Araldite) which is subsequently cured ; the electrodes are then cathode-sputtered or evaporated as for quartz.

4.9. Thermistors

Certain materials (e.g., silver sulphide and uranium oxide), having very large temperature coefficients of resistance when fused, are of considerable use for control purposes. Thermistors are available either as two-terminal resistors or indirectly heated and, besides applications such as thermostatic control, can also be used as circuit elements. In the feedback circuits of line amplifiers they can be used for automatic gain or equalization control.

Over certain ranges of current, thermistors have negative incremental resistance and, at frequencies which are low in relation to the thermal time-constant, they can be used as negative resistors, e.g., in oscillators. The stability of negative resistance is, as yet, hardly adequate for precision applications, but improved stability would permit of their use to offset losses in circuit elements such as inductors.

5. NEW DESIGN TECHNIQUES

The rational design of filters became possible in the first place only on an image-parameter basis, the effects of terminal mismatch and dissipation in the components being added as corrections. Zobel's original methods[9] were essentially "cut-and-try," the required results being achieved by combining sections of known characteristics. Cauer[10] subsequently showed how to design on the basis of image functions approximating to the desired characteristics, but his methods were never popular outside Germany and nearly all production designs have been based on Zobel's work. More recently, Darlington[11] has devised methods of design on an insertion-loss basis and has shown how the effects of dissipation can be allowed for in advance. Filter synthesis, on these lines, has been developed considerably by the Post Office and the characteristics of typical channel filters are included in Fig. 14.

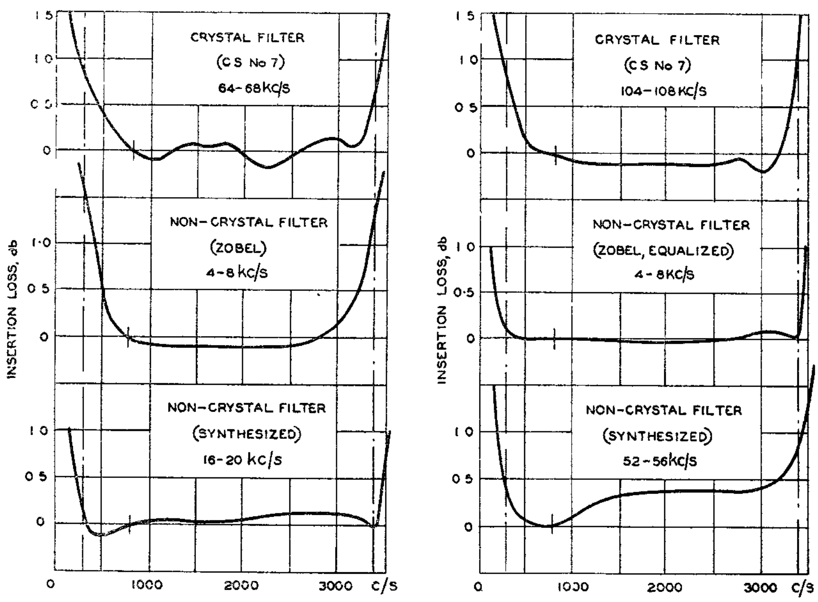


Fig. 14.—Telephone Channel Filters. Typical Pass-band Characteristics.

It is probable that these new methods will find application only in difficult and exceptional designs. They have not been applied to crystal filters ; indeed, the circuit restrictions imposed by the form of the resonator impedance may make it impracticable to synthesize this type of filter.

Methods of synthesis are now being developed for other types of networks and provide powerful tools in the design of equalizers, feedback amplifiers, precision transformers and psophometer weighting networks. With certain restrictions, networks may be designed to any desired limits.

Need for greater precision arises in transmission equipment proper and to a greater extent in measuring equipment. Difficulties arise in three stages, initial design, realization of designs with working tolerances and stability with time and temperature ; network synthesis assists with the first stage and may sometimes enable designs requiring maximum tolerances to be evolved. As an example of the precision required in measuring equipment, it is the objective to make transmission measurements between any two points in a coaxial system without removing circuits from traffic, with an overall accuracy of ± 0.25 db.

6. TELEPHONE CHANNEL EQUIPMENT—CRYSTAL v. NON-CRYSTAL

Filters for early 12-circuit carrier systems employed capacitors and inductors ; C.S. No. 5 used direct modulation to 12-60 kc/s, C.S. No. 6 used double modulation via 6-9 kc/s ; each transmitted frequencies 300-2600 c/s. Subsequently, the Post Office adopted American practice and C.S. Nos. 7 and 8 employ direct modulation to 60-108 kc/s using crystal filters conforming to C.C.I.F. standards.

Contemporary development in Europe has been with double-modulation systems which are also favoured by some British manufacturers. In view of the satisfactory results achieved with such systems it has been necessary to consider carefully the type of system to be developed to replace C.S. No. 7, now over ten years old. The use of quartz being ruled out, detailed consideration was given to the relative advantages of an E.D.T. crystal-filter system and a double-modulation non-crystal system. The decision was in favour of the E.D.T. system and it is useful to examine the reasons for this. The specified requirement for accommodation of four groups per bay proved practicable with each system and the required performance standards could also be met.

In considering double - modulation systems all possible methods of assembling 12 channels in the range 60-108 kc/s were reviewed ; the preferred arrangement was to assemble sub-groups of three channels at 12-24 kc/s (erect), the second modulation using carriers 84, 96, 108, 120 kc/s. The following table compares the advantages of this and a crystal system.

Advantages of Crystal System.	Advantages of Non-Crystal System.
1. Fewer components in channel equipment (10-15%). 2. 12 valves per terminal against a minimum of 17 and consequent lower dissipation. 3. Modulator levels permit of lower carrier power. 4. Lower estimated cost.	1. Better channel characteristics. 2. Lower carrier leak. 3. Fewer types of panel. 4. Seven carrier frequencies against 12. 5. Facility for introducing a music channel instead of a sub-group. 6. The sub-group unit can be used in other types of system. 7. Non - specialized technique could be applied more readily by new manufacturers in an emergency

Relative costs are debatable and probably depend on factory techniques. Since all manufacturers require non-crystal filters, a small factory would probably profit by concentrating exclusively on this type ; a large factory can produce both types economically. As an example of the versatility of a sub-group system, L. M. Ericsson[12] have recently standardized on such a unit at 6-18 kc/s, incorporating either three 4 kc/s or four 3 kc/s channels and this is used for every type of system produced. For the Post Office system, in which 12-channel groups are the smallest employed, it is argued that the advantages of the Ericsson system obtain ; if export requirements are taken into account the position is not so simple.

Space heating being a strong argument against double-modulation systems, it is of interest that both the French P.T.T. and Philips systems use only one valve per channel. French systems[13] employ both 12-60 kc/s and 60-108 kc/s primary groups, but audio and G.D.F. levels differ from those standardized here (Post Office G.D.F. levels were fixed by considerations of crystal systems). In the Philips system[14] the primary group is 252-300 kc/s, the first modulation being at 60 kc/s, using Ferroxcube filters ; this simplifies both modulators and channel-combining equipment and one valve gives adequate gain.

7. TELEVISION TRANSMISSION

The relative merits of television relay by radio and coaxial cable have yet to be assessed. For the London-Birmingham route, which was served initially by radio, special 1 in. coaxial pairs have been provided[15] with the ultimate object of transmitting frequencies up to 30 Mc/s or more for high-definition or colour television. They are now equipped to transmit a 3 Mc/s video band in the range 3-7 Mc/s using a 6 Mc/s carrier and vestigial upper sideband.

The C.C.I.F. recommendations are first being implemented between Birmingham and Manchester. The video band is double-modulated on frequencies 9.8 and 10.8 Mc/s to the range 1-4 Mc/s ; the 1 Mc/s carrier and vestigial lower sideband extending down to 500 kc/s are transmitted.

The advantages of erect over inverted sideband transmission are that:—

1. Since a greater amount of random noise can be tolerated at the higher video frequencies and receiving levels are limited by resistance noise, substantially lower transmitted levels are permissible.
2. The transmitted frequency range can be extended if desired.

The main disadvantage is potential interference from harmonics of the transmitted carrier, introduced by non-linearity.

8. POWER SUPPLIES

Twenty-one and 130 volt battery supplies have long been restrictive to design ; valve heaters are normally voltage rated and are liable to damage if series-connected ; anode voltage is often inadequate. Alternative proposals have always met with opposition ; V.F. telegraphs are unsuited to mains operation —momentary power failure may result in a wrong message—and voltages exceeding 150 have been opposed on grounds of personal safety.

The use of mains supplies, with mains simulation by a prime-mover as a reserve, has now been accepted, but to safeguard telegraphs a small floating anode battery will bridge the change-over period ; the thermal capacity of indirectly heated valves suffices to retain emission. Heaters will be in parallel and will be supplied from a transformer on each bay ; except for small installations anode supplies will be from central units. The normal anode voltage will be increased to 220 subject to precautions against damage to personnel ; pull-off dust covers will not be permitted and warning notices will be fitted.

On coaxial cable routes power (350 V, 50 c/s) is fed over the cable to two or three repeaters, the spacing of power-feeding stations for $\frac{3}{8}$ in. coaxial pairs being up to 30 miles. In America such stations are spaced at distances up to 165 miles, the feed being (nominally) constant current at 60 c/s, with repeater power circuits connected in series. The repeaters require considerably less power than our own and the power circuit is inductance loaded at each repeater station to reduce the attenuation.

9. SUBMARINE TRANSMISSION SYSTEMS

Following the successful introduction of submerged repeaters into the Anglo-Irish[16] and Anglo-German[17] submarine cables a standardized repeater has now been introduced for use in 0.62 in. coaxial cables in shallow water.* This repeater handles 60 channels in each direction, 24-264 kc/s outwards and 312-552 kc/s

* First used between Aldeburgh, Suffolk, and Domburg, Holland, in August, 1950, four repeaters in tandem.

inwards and has been designed to operate up to 10 units in tandem ; the spacing (about 16 nauts) gives 60 db. attenuation at 552 kc/s and a maximum distance of nearly 200 nauts can therefore be provided for.

It is now possible, therefore, to standardize equipment for submarine cable routes instead of tailoring each scheme individually and planning on the same general basis as for land cables will be possible ; with our insular position this is of considerable importance.

The cases of the new repeaters are little different from those of earlier units (Figs. **15** and **16**), but the form, as well as the detail, of the inner assemblies has been considerably modified in order to facilitate testing and inspection. Power (D.C.) is supplied over the cable from a constant-current generator which is necessary to avoid heater burn-outs under earth fault conditions. The power circuits of all repeaters are in series in the centre conductor, heater and anode circuits being in parallel, and for the units now under construction this requires a feed current of 0.7 amp. On a cable equipped with 10 repeaters the necessary 3000 volts will be supplied by a 1500 volt generator at each terminal. A very necessary development is long-life valves requiring low heater current ; heater voltage is of little importance. Ideally, the total voltage drop across the valve heaters in a repeater should equal the anode voltage, but such a design is unlikely to be realized for some time. Extensive tests on the cables indicate that little difficulty should be experienced

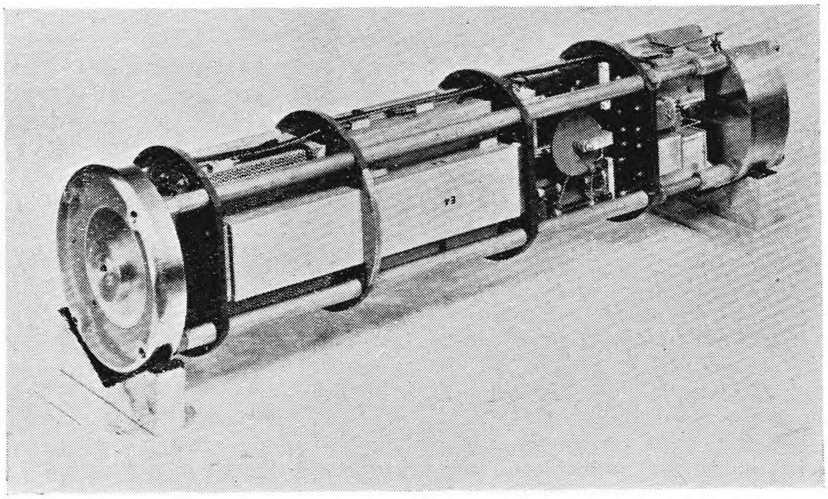


FIG. **15**.—60-CHANNEL SUBMERGED REPEATER FOR SHALLOW WATERS—INNER ASSEMBLY.

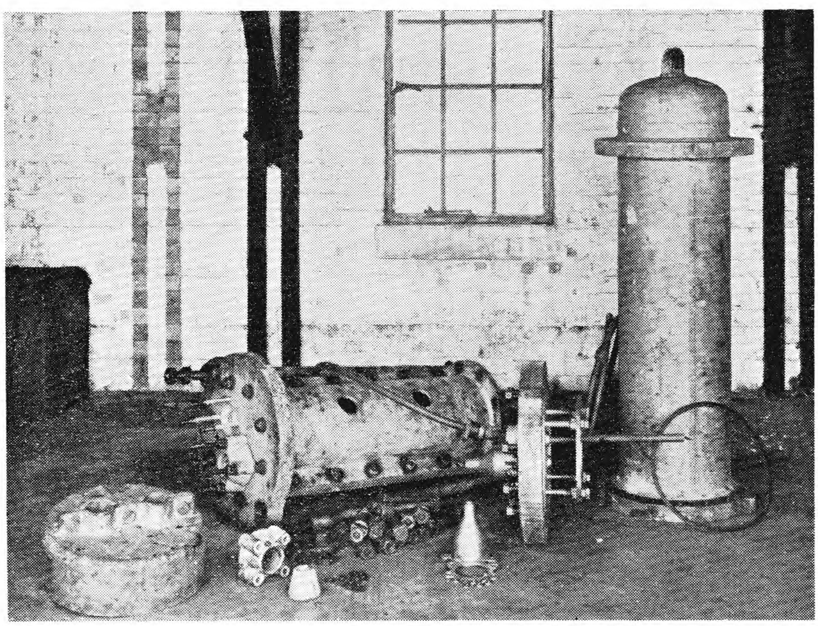


FIG. **16**.—60-CHANNEL SUBMERGED REPEATER FOR SHALLOW WATERS—OUTER CASING.

from breakdown at the power voltage except, possibly, from badly-made joints.

With tandem-operated repeaters it is important to provide for localizing both cable and repeater faults from the shore. For repeater faults, a method of pulse testing has been developed ; since different frequency bands are used in the two directions a frequency change must occur before a reflected pulse can be transmitted back and this is effected by non-linearity either in the amplifiers (near overload) or in silicon carbide resistors which can be switched across the output of each repeater. Using the latter it is possible to measure the working level at the output of any repeater from the shore station to within about 0.25 db.

For ocean cables, involving depths up to 3000 fathoms and pressures up to 4 tons/in^2, development is not so far advanced. In America, articulated units,[18] capable of passing over cable sheaves during laying and intended for transoceanic telephony, have been tested experimentally and parallel work is in hand here. The main development here, however, has been on repeaters for use in telegraph cables at frequencies below 10 kc/s ; the necessary bulk of equipment seems to preclude the use of the articulated units, which have an internal diameter of only about 1½ in. Rigid cases having an internal diameter of 8 in. are therefore being developed, primarily for Cable and Wireless Ltd. and an experimental scheme is in hand ; the design of glands for repeaters of this type calls for considerable skill and ingenuity. The insertion of repeaters in the older transoceanic telegraph cables, with a view to increasing their traffic handling capacity, has been considered but the low breakdown voltage of such cables precludes the use of such repeaters as would otherwise seem practicable. Owing to the great length of these cables and the high conductor resistance, development of long-life valves requiring very low heater current (say 50 mA) is a necessary preliminary.

The development of submerged repeaters generally is of great importance in the economic provision of transoceanic communications. For transatlantic telephony it should become practicable to provide bandwidths of 50-100 kc/s over cables having repeaters spaced at about 50 mile intervals. The maximum utilization of such channels would be essential for economic operation and devices which are capable of reducing the requisite bandwidth are important. Development of the vocoder[19] is still proceeding and this is still the most promising equipment of its kind ; its application to internal circuits is, however, improbable.

10. SHORTCOMINGS OF PRESENT AND PROJECTED SYSTEMS

10.1 Design

The coaxial system as now planned ultimately provides 960 channels per pair. These are spaced at 4 kc/s intervals except for small gaps between super-groups,* i.e., cable utilization is highly efficient. This is reflected in the cost of terminal equipment—close filtration is expensive—and makes difficult the extraction and re-introduction of groups and, more particularly, super-groups. Signalling equipment, too, represents a heavy charge on trunk circuits and a typical analysis of annual charges for a 300-circuit coaxial system 100 miles in length with 2 VF signalling is as follows:—

Cable	19.3%
Repeaters...	10.2%
Terminal Equipment	42.0%
Signalling...	28.5%

One half of this total is accounted for by maintenance charges. For a 960-circuit system the annual charges on terminal equipment (with signalling) will be about 90% of the total, falling to 50% on a 900 mile circuit.

The importance of this high cost of terminal equipment is generally recognized. In America it is now considered that the present type of coaxial system is appropriate only for long distances and a system with double-sideband transmission and integral signalling is contemplated for distances up to, perhaps, 200 miles.

This may be a pointer to future development here and the problem is now receiving attention. There would be some complications, however, in introducing a system such as this since it would utilize neither the present H.F.R.D.F. nor G.D.F. frequency bands and would conflict with plans for the general application of 2 VF signalling.

Some tentative details of the proposed new American system[32] are:—

1. 12 circuits per pair on 20 lbs./mile junction cable, repeatered at eight mile intervals. Cross-talk balancing networks are unnecessary.
2. Carriers spaced eight kc/s, transmitting both sidebands and a carrier voltage proportional to the signal, i.e., always 100% modulation.
3. Frequency bands 44-140 kc/s and 164-260 kc/s in the two directions on different cable pairs, e.g., within quad.
4. Frequency bands interchanged (" frogged ") at each repeater and sections equalized in pairs (only about four db. remains after self-compensation).
5. Compandors on each channel (this fits in well with 100% modulation—a parabolic demodulator gives automatic expansion).
6. Channel filters of very simple type.
7. Integral signalling at 3700 c/s.
8. An estimated cost only one-fifth that of a conventional system.

With such a system under development the A.T. & T. are proposing new standards for their coaxial system which will transmit either 1500 telephone channels or 3 Mc/s television + telephony in the range 0.3-8 Mc/s. The 60-300 kc/s super-group, never favoured by the Post Office and standardized mainly through American and German influence, is now considered undesirable. To accommodate this system,

* Opinion here is largely in favour of modifying the C.C.I.F. spacing to allow a considerable gap between two hyper-groups, each consisting of eight super-groups.

the repeater spacing for $\frac{3}{8}$ in. coaxial pairs will be reduced from eight to four miles and the additional super-groups will probably be added as a hyper-group with a gap of 20-30 kc/s.

The use of through-group filters to extract and reintroduce groups at the G.D.F. is now standard and, although expensive, these filters are generally satisfactory ; the technical difficulty and cost would, however, be greatly reduced if gaps were provided between groups. The switching of super-groups in the range 312-552 kc/s has long been highly desirable, but a through-super-group filter to meet the requirements has proved extremely difficult and no entirely satisfactory unit has yet been produced. The technical problem now appears to be near solution, but it is probable that the filters will require temperature-control. It is believed that no other administration has solved this problem directly although indirect methods have been devised ; the vast amount of equipment which has been used in these arrangements is a clear indication of the importance of the facility provided.

The provision of music channels in wideband systems, while clearly desirable, is not straightforward. They can be introduced either in the terminal equipment or at the G.D.F. as proposed for the Post Office system. With either method it is necessary to reject frequencies 30-50 c/s on one side of the carrier while accepting similar frequencies on the other side. There are several possible ways of doing this, none of them easy ; the most elegant is the single-sideband modulator[20] which requires quadrature supplies of both the carrier and signal frequencies. The design of phasing networks for the band of music frequencies forms an interesting application of network synthesis; a suppression of 40 db. involves a differential phase accuracy of 0.6°. In America a crystal filter[21] has been designed to effect the sideband filtration directly; operating at a carrier frequency of 88 kc/s, it includes 22 double crystals.

Even when suitable equipment has been designed to provide the music channels, the problem remains of maintaining circuit noise within acceptable limits and some concern is felt in this connection.

10.2 Maintenance

Difficulty has always been experienced in maintaining appropriate transmission standards. Variations in circuit equivalents have been large and erratic and, apart from changes of line attenuation with temperature, reside in repeater and terminal equipment. With non-feedback amplifiers, valves and power supplies were usually suspect, but the trouble persisted even with feedback and is now recognized as the effect of considerable numbers of imperfect connections—dry joints, intentional and otherwise. Sometimes disconnections are complete, more often contacts are a variable fraction of an ohm ; at one time they were so numerous as to cause serious misgivings over carrier working generally with its great increase in complexity of equipment ; a really determined attack on the problem during the last few years has, however, yielded substantial improvements.* The number of faults on any circuit is roughly proportional to the number of valves involved and for circuits 100-200 miles in length the reported fault rates for audio, 12-channel and coaxial circuits are approximately in the ratio 1 : 2 : 4.†

A trunk circuit involves some 10^4 soldered connections and a minimum standard for dry joints should be about 1 in 10^4, with 1 in 10^5 desirable. In 1947, the soldered connections in some deliveries of equipment were specially examined after completion of all normal tests and inspection ; the number of defective connections was, on an average, 1-2%, with a maximum of 5%. A large proportion of such faults are revealed during acceptance tests in the field, but, even so, an overhaul of working transmission equipment resulted in the clearance of about half a million dry joints, an estimated proportion of 1 in 10^2 to 1 in 10^3. Special vibration-testing techniques employing new types of fault-detectors operating at audio and carrier frequencies are expected to reduce the proportion of faulty connections to 1 in 10^4 or less before new equipment is put into service. Many faults take years to develop and second overhauls of working equipment reveal disconcerting numbers of new faults.

Clearly, the incidence of faulty soldered joints can seriously restrict development and a determined effort to minimize this trouble is essential before more advanced systems can be introduced; it is hoped that measures already in hand will prove adequate.

Other sources of dry connections are valve sockets and U-links. With more reliable valves and new servicing methods, valves will normally be soldered in. Existing types of U-links are definitely untrustworthy showing contact resistances up to 10 ohms or more, but it has not yet been established whether newer types are sufficiently reliable. Blind sockets must be avoided owing to difficulties in plating and cleaning and in general, flat-bladed links in spring sockets are preferred.

It is now becoming usual to consider circuit equivalents statistically and it has been proposed that, as a target, the standard deviation should not exceed 1 db. with respect to the nominal value. This will involve considerable improvements over present standards whereby lining-up limits are ± 2 db. and departures up to ± 4 db. are dealt with only on a non-urgent basis.

Even if national and C.C.I.F. requirements are reformulated on a statistical instead of a " maximum adverse " basis there are strong arguments for reducing switching losses and increasing stability margins at switching points ; these are likely to lead to at least a partial adoption of four-wire switching. This should have no important repercussion on transmission equipment except to aid in the elimination of echo suppressors, which should have no place in high-velocity networks although they may be required on low-velocity extensions. The elimination of echo-suppressors as stabilizing devices is extremely desirable.

Automatic gain control on each super-group of a coaxial system has been tried experimentally[22] and is

* In three years the overall average has been reduced from 3 to 1.5 faults/circuit/annum.

† The position is probably worse than this as faults on carrier circuits are probably not fully reported.

likely to be standardized ; it may be extended to groups on 12-circuit systems. Alternatively, or in addition, automatic control of repeater output levels may be adopted, particularly on coaxial routes.

The possibility of effecting an automatic line-up of every connection, after it has been established, has not been overlooked, but this could well come outside the province of the transmission engineer.

11. DEVELOPMENT OF LONG-LIFE VALVES

The demand for valves having greater reliability is now becoming urgent. Failures can be divided into two classes:—

(*a*) " Catastrophic " failures of envelopes, heaters, etc.

(*b*) Emission failures in normal usage.

The first can be countered only by more careful production and inspection ; the second opens a considerable field for research.

For submerged repeaters in ocean cables only a small percentage of failures should occur in 20 years and a very long mean life with a small deviation ratio is necessary ; even for shallow water repeaters " 5-year " valves are barely adequate and double this life is highly desirable. For soldered valves to be successful, catastrophic failures after fitting must be few and the mean emissive life should desirably reach 20-30,000 hours, a value already achieved by some types of valves now in common use. The statistics of valve life may well determine the extent of the application of electronic techniques to line equipment ; terminals involving 1000 or more valves have already been used for special purposes.

For early line equipment special valves were employed and, although of low performance, some types had phenomenal lives. For example, when Aldeburgh Repeater Station was dismantled in 1940, some of the original valves (1923) were still in service and to acceptance standard. Nowadays, transmission equipment utilizes valves primarily designed for other purposes ; long and uniform performance is prized by neither the valve manufacturers nor the main classes of user but a return to special types is discouraged for strategic reasons.*

The Post Office Research Station has taken a special interest in the development of long-life valves. The underlying principles are now fairly well understood and means have been devised for estimating emissive life from tests lasting only a few thousand hours. Valves made at Dollis Hill now have substantially better emissive performance than any commercial samples and it is hoped that the problem is well on the way to a satisfactory solution. Eventually, of course, the techniques developed must be applied commercially.

* Since writing this paper there has been a widespread realization of the necessity for " ruggedizing " valves for certain military requirements.

12. USE OF OTHER METHODS OF MODULATION

In line transmission we are almost exclusively concerned with amplitude modulation of sinusoidal carriers, usually as a means towards frequency translation. In radio transmission other types of modulation are employed, necessitated and justified by:—

(*a*) the lower signal/noise ratios experienced ;

(*b*) fading due to multi-path transmission ;

(*c*) the greater bandwidth which can often be made available.

We shall now briefly examine these methods and consider their potential application to line transmission. There are basically two types of modulation, amplitude- and time-modulation, the latter embracing frequency- and phase-modulation. An amplitude-modulated sine wave can be chopped into a series of pulses for the purpose of interlacing other similar signals on a time-sharing basis (time-division multiplex or T.D.M.). Such an arrangement is called pulse-amplitude modulation (P.A.M.), but it is important to note that " pulse " refers, not to the type of modulation, but to the form of the unmodulated carrier. It is convenient to regard the appropriate D.C. pulses as a sub-carrier which can be modulated by the " message " either in amplitude or position (i.e., time). The modulated sub-carrier can then amplitude modulate a sine wave carrier if required.

12.1 Frequency Modulation

F.M. requires a greater bandwidth than A.M. but, in return, yields two advantages:—

(*a*) improvement in signal/noise ratio ;

(*b*) since severe limiting of the received signal causes no distortion, variations of circuit attenuation can be eliminated.

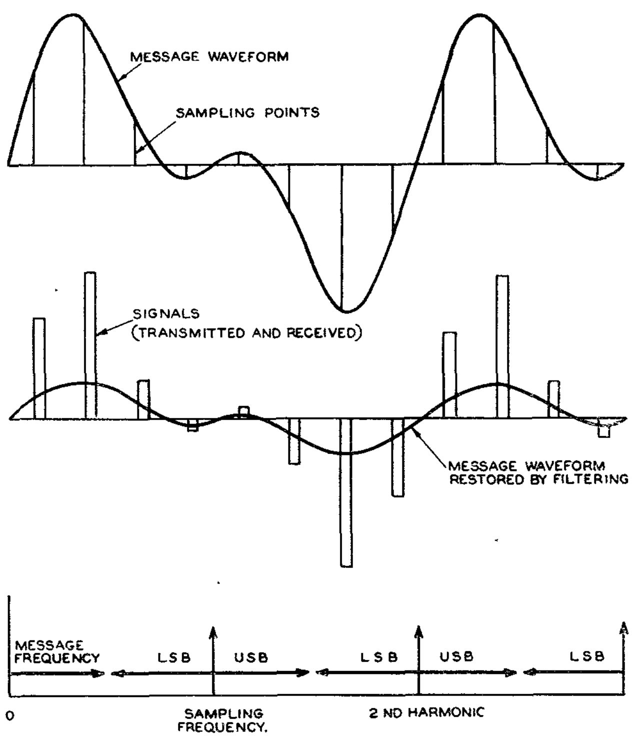
The improvement in signal/noise ratio is in direct proportion to the bandwidth consumed, increasing at 6 db. per octave ; the stabilizing effect is independent of bandwidth. On lines, where bandwidth is expensive, this rate of exchange between bandwidth and noise is not worthwhile and the only attractive feature of F.M. is the stabilizing effect, which can be achieved with quite small deviations. Under such conditions only the first F.M. sidebands are important and the required bandwidth is 2 × (deviation + message bandwidth).

There is no indication of any future application of F.M. in telephony, but it is already usual for fascimile picture transmission, where signal stability is of major importance, and may be adopted for multi-channel V.F. telegraphy. New telegraph systems designed on this basis have much less distortion than the present standard A.M. system, but a re-examination of A.M. technique suggests that substantial improvements can be effected here also. The future of F.M. telegraphy over lines is, therefore, still undecided.

12.2 Time-division Multiplex

All present-day line transmission systems are frequency-division multiplex (F.D.M.) systems, i.e., the channels share a common transmission path on a frequency basis. T.D.M. pre-dates F.D.M. being used in D.C. telegraphy (e.g., Baudot); there is now a possibility that it may return in a modified form for telephony.

Telephony by T.D.M. involves the principle of sampling—since the equipment cannot "look at" the message continuously, how often and for how long must it do so? In order to avoid interference with the sidebands generated by chopping, the sampling rate must exceed twice the highest message frequency. (Fig. **17**). The sampling time can be as short as is required for the level to be read since "holding" circuits are necessary; with modern equipment a fraction of a microsecond suffices.



SPECTRUM OF SIGNALS WHEN MESSAGE IS SAMPLED AT TWICE THE HIGHEST MESSAGE FREQUENCY

Fig. **17**.—Principles of Sampling.

A T.D.M. system with "square" pulses is intrinsically free from interchannel interference, but transmission over an imperfect medium causes pulse distortion and hence mutual interference. Freedom from interference can also be obtained if the principle of sampling is also applied to the received pulses and if these pulses are of such a shape that every other pulse is passing through zero at the sampling instant. One pulse shape which meets this requirement is shown in Fig. **18**; this corresponds to a very short pulse which has passed through an ideal low-pass filter, i.e., a filter having uniform attenuation and a linear phase-shift characteristic over the entire pass-band.

Imperfections of the transmission system, which will cause pulse distortion are (*a*) bandwidth restriction; (*b*) non-uniform attenuation in the pass-band, and (*c*) non-linear phase characteristics in the pass-band. A transmission system with the characteristics of an ideal filter has a minimum degree of imperfection and with such a transmission system it is theoretically possible to operate a T.D.M. system with the same economy of bandwidth as for an F.D.M. system, i.e., message bandwidth × number of channels. The actual bandwidth which must be allocated to a T.D.M. system depends on the permissible degree of interference, pulse shape, type of modulation, etc.

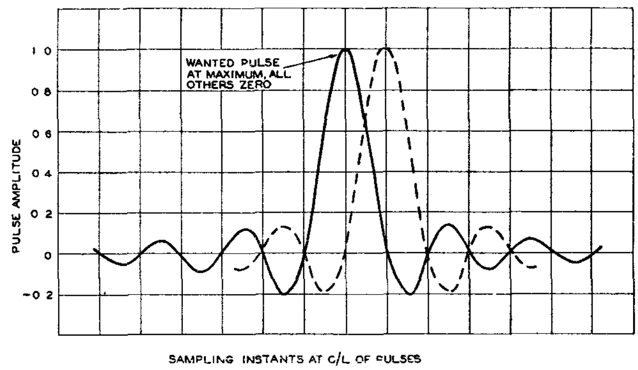


Fig. **18**.—Short Pulse through an Ideal Low-pass Filter—$\frac{\sin x}{x}$

Fig. **19** shows that, for "square" pulses amplitude modulated, an allowance of twice the message bandwidth per channel, with transmission characteristics corresponding to an ideal filter, give an interference ratio of only about 20 db. Pulse position modulation (P.P.M.) now favoured in radio telephony gives no improvement in this respect and it is necessary to use shaped pulses and to detect these with short, carefully adjusted gating pulses in order to obtain a bandwidth economy approaching the theoretical ideal. Even with the best possible arrangement, however, it is difficult to obtain adequate freedom from crosstalk unless considerable bandwidth margins are possible.

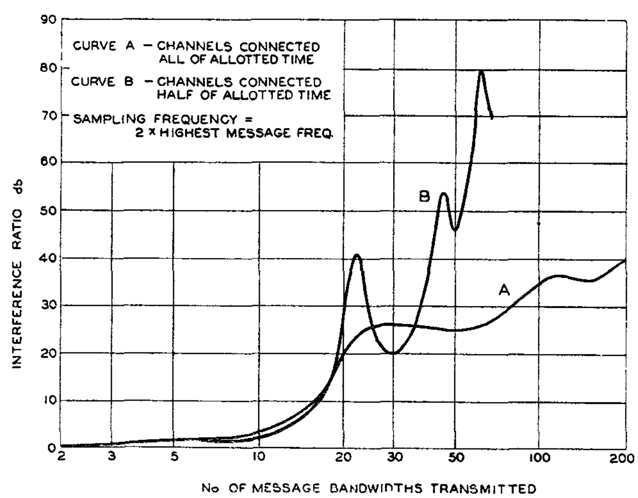


Fig. **19**.—10-Channel T.D.M. System—Crosstalk between Adjacent Channels.

It is to be noted here that the success of T.D.M. in telegraphy resides in the necessity for recognizing only the presence or absence of a pulse ; using modern equipment this can be effected reliably with a peak signal little more than twice the peak noise.

12.3 Quantizing

If a continuous range of message levels is transmitted, noise must always cause distortion. If, however, we are content to identify only certain discrete levels, noise of less than a certain magnitude can be positively rejected by signal regeneration. The principle of identifying a sample* by a level in a discrete series, is known as "quantizing."[24] The sequence of events is shown in Fig. **20** which indicates the origin of the "quantizing noise" which accompanies the received signal ; the greater the number of levels the lower is the magnitude of this noise which, with a complex signal, resembles resistance noise. The

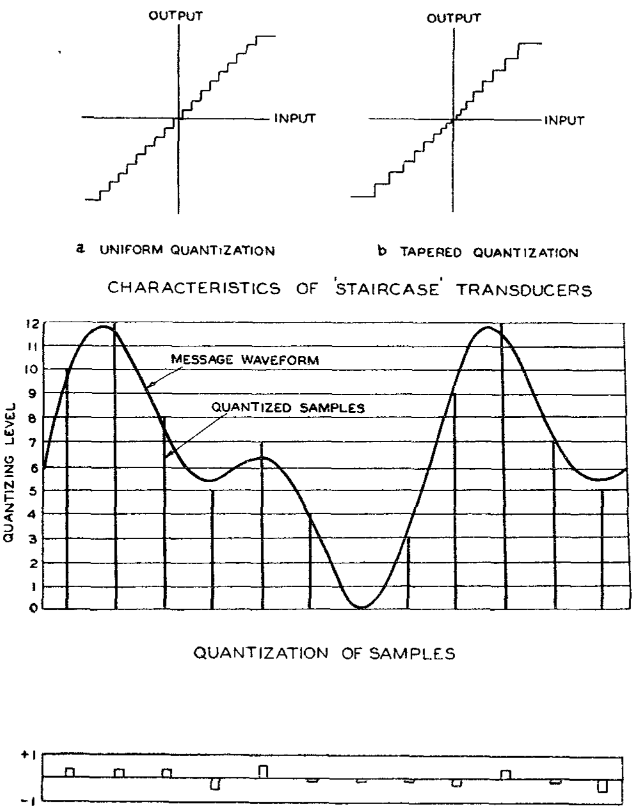


FIG. 20.—PRINCIPLES OF QUANTIZING.

number of quantizing levels necessary depends on the type of message to be transmitted, i.e., on the permissible level of quantizing noise. The quantizing steps are usually tapered, being small at low levels and large at high levels. Unlike normal systems, the ratio between the signal and the distortion (i.e., quantizing noise) is reduced with the signal level, and, ideally, there is no noise in the absence of a signal.

* Quantizing without sampling is, of course, possible but would seem to have no practical application.

12.4 Pulse-code Modulation

The simplest quantized signals are binary digits, i.e., on—off signals, and any quantized level can be expressed as a sequence of binary digits (binary code). Thus, if 2^n quantizing levels are used, the correct one can be identified by the presence or absence of n pulses. For example, the first pulse could indicate that the amplitude is, or is not, greater than $\frac{1}{2}$, the second pulse, that the residue is, or is not, greater than $\frac{1}{4}$, and so on. This is known as pulse-code modulation (P.C.M.).[25] For commercial speech at controlled volume, $32 = 2^5$ levels are ample and can be defined by five binary digits ; these can be positively identified if we allow about 20 kc/s per channel (sampling frequency 8 kc/s). If the mean speech level varies widely, as in line telephony (A.V.C. involves voice-operated stabilizing devices) 32 levels are inadequate and 128 levels (7 digits) have been used, requiring 28 kc/s per channel.

12.5 Modern Communication Theory

Much has been done in recent years to clarify the general theory of the transmission of information. Following work by Nyquist and Kupfmuller, Hartley enunciated in 1928 a partial theory which went no further than stating that the amount of information which can be transmitted is proportional to time and bandwidth. In introducing frequency-modulation Armstrong showed that bandwidth can also be traded for signal/noise ratio at the rate of 6 db. per octave.

Modern studies have shown that information can be closely identified with entropy, which is a measure of the degree of random in an atomic system ; information, being the antithesis of random, is properly classed as negative entropy. This avenue of approach has been explored by Shannon[26] who has reformulated Hartley's Law as follows:—

$$M = \left(1 + \frac{P}{N}\right)^{TW}$$

where M is the number of independent message items which may be identified in time T, bandwidth W and signal/noise ratio $\frac{P}{N}$ (power units). If $M = 2^S$, the corresponding number of binary digits $S = TW \log_2 \left(1 + \frac{P}{N}\right)$ and the number of binary digits which can be handled per second is $W \log_2 \left(1 + \frac{P}{N}\right)$

When $\frac{P}{N} >> 1$, this becomes $W \log_2 \frac{P}{N}$

$= \frac{1}{3} \times$ Bandwidth $\times$ Signal/noise ratio in db.

This leads to the surprising conclusion that, in an ideal system, one octave increase in bandwidth should double the signal/noise ratio *in decibels,* i.e., if a system has a signal/noise ratio of 30 db., doubling the bandwidth should increase this to 60 db. and not merely to 36 db. as in F.M.

P.C.M. proves to be a multiplicative system strictly in accordance with Shannon's Law. Fig. **21** shows the theoretical minimum bandwidth for P.C.M. using 5-unit code under various noise conditions ; this is actually less than the message bandwidth if the signal/noise ratio exceeds 30 db. A binary digit is identifiable with a signal/noise ratio of 6 db. and for 5-unit P.C.M. we must recognize say 40,000 digits per second ; the theoretical bandwidth is then 17 kc/s.

If the signal/noise ratio is 30 db. (voltage ratio 1/32) we can theoretically identify four independent sets of binary digits having amplitudes $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ and 1/16. Thus a bandwidth of 16 kc/s could provide four independent speech channels with P.C.M. as with F.D.M. A simpler method of achieving an equivalent result would be to transmit quantized levels directly, without conversion to P.C.M.

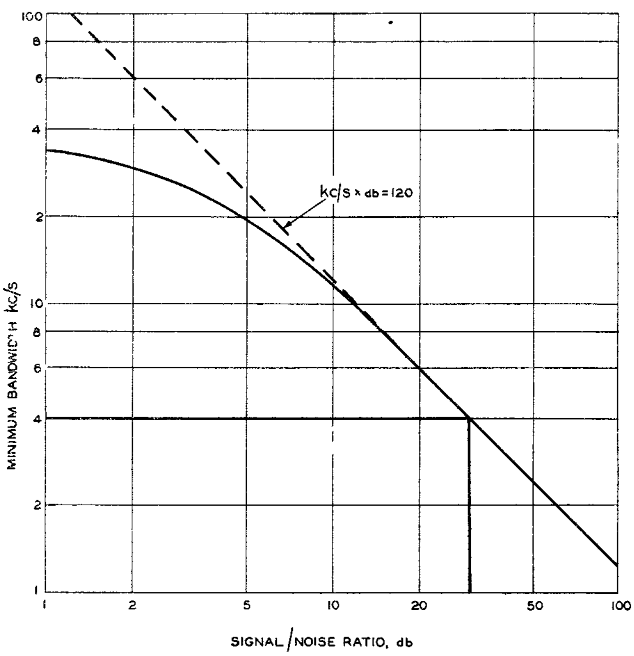


FIG. 21.—THEORETICAL MINIMUM BANDWIDTH FOR 4 KC/S SPEECH CHANNEL USING P.C.M.

12.6 Possible Application of P.C.M. to Line Communication

It is too early to foresee the impact of these new ideas on line telephony, but it is useful to examine some of the advantages which might accrue from the use of P.C.M. A system could be planned on any of three bases:—

1. Assembly of P.C.M. channels on a time-sharing basis to the capacity of the transmission system.
2. Assembly of P.C.M. channels into smaller units which could be transmitted together on a frequency-sharing basis.
3. Assembly of channels on a frequency-sharing basis (e.g., the present 12-channel groups) and the application of P.C.M. to such groups.

Division of the available transmission band on a frequency basis imposes a linearity requirement or, if signals are regenerated instead of amplified—a major attraction of P.C.M.—filters are required at each regenerator. Nevertheless, an experimental system as (2) has been built in America for use on a radio link.[27] Integration of a P.C.M. system with the present F.D.M. systems might impose requirements which make (3) desirable, but the broad features of a P.C.M. system can best be examined in relation to (1).

We will consider then the potential utilization of a $\frac{3}{8}$ in. coaxial pair with regenerators at the present repeater spacing of six miles. Using the same output valve as that required for 960-channel F.D.M., the transmitted level could be +25 db. and it would be possible to utilize frequencies up to about 20 Mc/s (received signal level −77 db.* at a point where the random noise level is −95 db.). Using 7-unit P.C.M., some 700 channels could be provided, about 75% of what is possible using F.D.M. The pulse-repetition frequency would be 4×10^7 per second (0.025 μS pulses) and a considerable degree of interference from adjacent pulses would be permissible.

At the present time the scheme is probably impracticable, but progress in electronics is rapid. Pulses of the requisite duration can already be generated and associated techniques are rapidly being developed. Ingenious use is being made of special beam-deflection tubes as pulse generators and distributors ; indeed, special C.R.T. development would seem to be the most promising approach to the problem. Pulse-code modulation and demodulation can be carried out reliably either with simple valve circuits or a special beam tube[28] and the total amount of terminal equipment involved is likely to be less than for the present system.

The likely advantages of multi-channel P.C.M. systems over present F.D.M. systems are:—

1. The flexibility by which any number of channels may be introduced or blocked, selection on a time basis being possible with great precision.
2. The flexibility by which circuits of increased bandwidth, e.g., music circuits, could be accommodated.
3. The use of regenerators ensures that signal impairment is not increased by distance.
4. The equivalent of D.C. signalling could probably be provided.

12.7 Use of Wave Guides

A great deal of work on guided waves is proceeding and it seems probable that the economic design of trunk systems will eventually become practicable. For this purpose attention is focused on transmission of TE_{01} waves in hollow, circular guides, the only

* It has been demonstrated that with existing circuit technique a ratio of 18 db. between peak signal and R.M.S. random noise is satisfactory.