The Early Development of the British Underground Trunk Telephone Network

by

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1. INTRODUCTION : TRUNK TELEPHONY IN 1900

The British underground trunk telephone network really came into being only after the First World War, and until then practically all trunk lines, and certainly all very long ones, were comprised of overhead lines using wires of very heavy gauge, up to 800 lb/mile. (1 lb/mile = 0.28 kg/km.) There were short lengths of underground cable interspersed in many of these lines where they had to traverse large towns, but these were rightly regarded as undesirable hindrances to good telephone transmission. Some of the problems of transmission, and also the reasons why Britain was somewhat tardy in having a trunk system, have been mentioned in my previous paper[1], so all that need be said here is that it was in 1896 that a proper trunk telephone network was established in Britain when the Post Office acquired a monopoly of trunk communication, took over the company long-distance lines, upgraded them, and extended the network by building many new lines. After that the British trunk telephone system developed comparably with that of the rest of Europe, and most of the developments this paper is concerned with were paralleled in many of the other European countries.

It must be appreciated at the outset that there is a fundamental difference between the electrical characteristics of open line and cable. The resistance of the wires can be made the same by using the same gauge of wire, but the other three important parameters – electrical leakage, or 'leakance' (measured in reciprocal ohms or 'mhos'), capacitance (microfarads), and inductance (henries), all usually measured per mile, differ greatly. Leakance, while hopefully constant in a cable, is at the mercy of the atmosphere in an open line; capacitance in an open line is small and inductance is relatively large because of the wide spacing of the conductors, whereas in a cable the capacitance is high and the inductance is low because the wires are close together. Not only does it follow that the transmission loss in a cable is much larger than in an open line, but as the cable has a greatly different 'characteristic impedance' from the open line, the insertion of sections of cable in a long open line causes large reflection losses. So it is clear why cable sections were so undesirable.

Another difficulty in the period around 1900 was the absence of any proper way of measuring the transmission properties of a telephone line. The history of transmission theory and transmission measurement really requires a separate paper. Methods were developed in the first decade of the twentieth century for measuring the transmission of a line by aurally comparing the speech over a line looped back on a similar line with that received through an artificial cable which could be adjusted in steps. The practical unit of transmission became the 'mile of standard cable'. By good fortune, this unit turned out to be very close to 1 decibel (dB) when that more exact unit was introduced in the 1920s. (It was, of course, derived from the bel, named after A.G. Bell.) Work was also done on the understanding of the bandwidth requirement of speech. Instrumental methods of measurement were slowly developed.[2]

Theoretical work on transmission used the 'attenuation constant' as the principal criterion of transmission; this was basically the natural logarithm of the ratio of sent to received current. Its unit was later called the neper (after the French mathematician Napier), and again, fortunately, the decineper was not very different in magnitude from the decibel. (1 dN$\simeq$ 0.87 dB.)

The London-Glasgow trunk lines (about 450 miles or 720 km long) used the heaviest copper conductor, nearly 5.7 mm diameter and weighing 800 lb/mile, and with normal spacings and summer weather had a transmission loss in the open lines of what we would now call about 9 dB. The odd lengths of cable which had to be used increased this to about 13.5 dB.[3] Shorter lines achieved the same standard of transmission using lighter wires. By this time all conductors were of copper, the use of iron having been abandoned.

2. EARLY UNDERGROUND CABLES FOR TELEPHONY

2. 1. **Tentative use of cables for telephony.** By the time the telephone was introduced commercially in 1877,[4] telegraph cables were used world-wide, mainly for crossing the oceans, seas, and rivers, but also to some extent underground. They were insulated with gutta-percha. Thus, when in certain areas the civic authorities objected to overhead telephone wires, as in Newcastle upon Tyne and Sunderland, the telephone companies and the Post Office (often in mutual competition) tried to use gutta-percha cables for telephony. These cables, however, had far too large a capacitance per mile for satisfactory speech transmission; tests made by Post Office staff at Newcastle and Sunderland in 1882 showed (among other very interesting – even curious – results) that even two miles of cable markedly worsened articulation, four miles permitted conversation but prevented the transmission of any actual message, and eight miles made communication impossible.[5] Nevertheless, such cables were in general use in the North East of England for subscribers' lines.[6]

Attempts were made to improve the design of cables, and one interesting type was the oil-filled cable of David Brooks; a short length of this was used for telephony and telegraphy in London between 1880 and 1889, but it was not successful.[7] (In the next decade, Brooks's system was much more successful when used for power cables.) A more successful type was the cable introduced by W.R. Patterson[8] in 1881 and widely used in the U.S.A., although hardly used at all in Britain. In this cable, the wires were at first covered with cotton or jute, but paper was used quite soon, with gas-impregnated paraffin pumped into the cable after laying. In Britain, as well as in other countries, a rather rigid so-called 'bituminous cable' was used up to about 1890; it had cotton covering to the wires, and was impregnated with a heavy distillate of petroleum.[9] It was made by the Fowler Waring Cable Company, which was later, in 1897, acquired by the Western Electric Company. Although the Brooks cable used iron tubes, the Patterson and Fowler Waring cables used lead (or lead-tin alloy) sheaths.

Far more experimenting with telephone cables was done in the U.S.A. than in Britain, and an excellent account of this work is given by Rhodes.[10]

2. 2. **Paper-insulated air-space cable.**[11] It was apparent during the first decade of telephony, in spite of a lack of a proper understanding of telephone transmission, that the main factor which made cable unsuitable for telephony was the high electrostatic capacitance resulting from the insulating materials used. This led to the rapid attenuation of the higher frequencies of speech, which became unintelligible before it became inaudible as the length of line was increased. J.A. Barrett of the American Telephone and Telegraph Company (the 'Long Distance Company' of the Bell System) proposed in 1889 the use of manilla paper tape, wound on spirally, as the wrapping for the conductors and demonstrated its success in lowering capacitance. Patterson, already mentioned, thought, correctly, that the lower capacitance was due largely to the fact that air was retained in the pores of the paper in spite of impregnation, and that best results would be obtained if the paper were not impregnated at all. This did not at first appeal to telephone engineers, who naturally feared the leakage of dampness into the cable through faulty joints in the lead sheath. However, the reduction of capacitance from the hitherto best value of about 0.20 microfarads (μF) per mile to about 0.08 μF/mile was an improvement which could not be ignored for long. Paper-insulated, air-space cable had come to stay by 1891. The problems of keeping it dry internally were solved by various improvements of technique, the main one being the improvement of the sheathing to avoid corrosion and other damage; a 3 per cent addition of tin to the lead was very effective in this regard. The drying-out of a cable during jointing and terminating was effected by the use of hot powdered lime, until near the end of the 1890s a process of dessication by the circulation of dry air was introduced.

Cable was used during all these years of development only for subscribers' lines, very short inter-exchange lines, or very short interpositions in long-distance open lines. A great stimulus to the increase in cable mileage, in Britain as in the U.S.A., was the conversion in the mid 1890s of subscribers' lines (and other lines too) to the metallic-loop system in place of the single-wire with earth return that had been so widely used for reasons of economy, although technically thoroughly unsatisfactory. A doubling of the huge mazes of overhead wires which disfigured most towns, just to provide metallic loops, could not have been tolerated. Consequently large mileages of cable were manufactured. In 1897 nearly 6500 miles of conductor were installed in paper-insulated cables in Britain by the Post Office alone,[12] and the telephone companies must have installed much more. Conductor size was generally 20 lb/mile and cables could have up to 204 pairs of conductors within a maximum cable diameter of 2.5 inches. The principal manufacturers were the Fowler Waring Company (from 1897 part of Western Electric) and the British Insulated Wire Company. Cables were not armoured but were laid in ducts, by this time usually of iron or of stoneware.

2. 3. **The London-Birmingham cable of 1897-99.** The first long-distance underground cable to be laid in Britain was that between London and Birmingham, completed in 1899. Its importance in the history of electrical communications in Britain is therefore great. Consequently it is very frustrating that the records which have survived are not entirely satisfactory. For example, it is not clear whether it was intended to be a combined telephone and telegraph cable or merely for telegraphy alone. The letter from the Secretary of the Post Office to the Postmaster-General, dated 7 Dec. 1896, asking for the first instalment of the total estimated cost of £165,000, does not mention telephony specifically, giving as the reason for the cable that:

> the aerial lines are becoming more and more crowded, and the necessity for an alternative route underground is becoming every day more urgent.

Yet a published article[14] refers to the 'telephone cable', and a later letter from the Secretary to the P.M.G. also refers to the London to Birmingham *telephone* cable.[15] Extensive experiments on the cable with telephony (and telegraphy simultaneously on other wires of the cable) showed that

> although telephonic speech was possible between the two places [London and Birmingham], there was not sufficient margin to permit of its use for commercial purposes....[16]

These experiments were under the direction of J. Gavey, who, having become Engineer-in-Chief of the Post Office soon afterwards, gave a Presidential Address to the Institution of Electrical Engineers in 1905 in which he discussed this cable at some length without ever mentioning its intended or possible use for telephony.[17] Although the London-Birmingham cable was authorised as an operational 'alternative route underground', there is little doubt that knowledge of long-distance cable work was so slight that the project was really an experiment. This is brought out in the letter from the Secretary of the Post Office to the P.M.G. of 8 July 1898,[18] which is so interesting that a lengthy quotation is worth while:

> The dry core cable for the new trunk underground line to Brimingham being of a new description, the manufacture of the first 60 miles was entrusted to the British Insulated Wire Company, the holders of the patents, at the price of £880 per mile. After some 30 miles had been made, it was found desirable to modify the specification and the Company reduced the price for the balance of the order to £800 per mile, certain short lengths of the cable which did not quite [meet] the old specification being charged for at the further reduced price of £700 per mile. The new specification is for a type of cable which is outside the patent and it was therefore possible to invite all the manufacturers of this class of cable, five in number, to compete for the supply of the second 60 miles to complete the London-Birmingham section. All five firms have responded, the prices being Western Electric Co., £740 per mile, B.I.W. Co. £750, Henley Telegraph Works £759,,Siemens Bros. & Co. £814, Glover & Co. £832. Although the W.E. Co.'s tender is the lowest, it is recommended for the following reasons that the order for the 60 miles be divided equally between that Co. and the B.I. Co. whose tender is the next lowest:- 1. The Department will have the security of two sources of supply.... 2. The W.E. Co. not having supplied the Department with cable of this type, their ability to do so is not absolutely assured. 3. The B.I. Co..... can be confidently relied upon to execute further contracts satisfactorily.

The P.M.G. agreed. This cable had 76 wires of 150 lb/mile; in the first section they were laid up in fours, but in the revised specification they were in pairs. Each wire had a longitudinal wrapping of paper and a strip of paper separated the two wires of each pair. The pairs were twisted in a 'lay' of 12 inches, and assembled in four layers of 1, 6, 12, and 19 pairs to make up the complet cable, which, after drying-out, was sheathed in lead of thickness 0.16 inch, giving an overa diameter just over 2.5 inches. It was drawn into 3-inch iron pipes. It involved 125,476 'carefull soldered wire joints' and 1651 plumber's wiped joints in the lead sheathing. In 1900 the E. in C reported:[19]

> The difficulties due to electrical induction which, as was anticipated, at first gave complete "over-hearing" on the telephone between all the wires of the cable, have been overcome to a marked degree, and the 8000 telegraphic and telephonic observations which were recorded during the protracted experiments have not only led to the development of a system of connections at the various testing points which practically removes the difficulties, but have also resulted in the design of a new type of cable which, it is hoped, will eliminate the defect without necessitating special connections. Cable with conductors twisted with varying lengths of "lay" is now being manufactured with this object.

This was over-optimistic, for, as we have seen, the idea of telephone working on this cable ha to be abandoned. However, we see the genesis of the idea of selective cross-connections for balancin out crosstalk,[20] which became important in later years. The crosstalk was mainly between adjacer pairs of wires, and the selective (i.e. not systematic) crossing of wires at jointing points was confine it is believed, to the four wires of each quad where quad-type cable was used. The process of selectio was based on the cancelling-out of unbalances over a fairly long length of cable. In the pair-type cabl crosses were made to ensure that no two pairs ran adjacent to one another for more than 1 per cent of the length of the route. (The "quad" type of cable – later called star-quad – wa one in which the four wires making two pairs, or metallic loops, are laid and twisted togethe so that the cross-section shows the four wires at the corners of a square; if then the pairs ar made from diagonally-opposite wires, there is in principle no mutual crosstalk. This scheme wa apparently invented by Oliver Heaviside in 1880; the use of twisting is even older.[21])

No further information on the improved cable has so far been found. The undergroun route was extended northwards to Glasgow during the subsequent three or four years, and th new cable contained an additional layer of 29 single wires (insulated) within earthed copper screen it was, however, devoted entirely to telegraphy.

One senses a defensive guardedness and lack of openness in all the records of this importan pioneering project. There was no need to be ashamed of the work, however; the problems o working telephone circuits in the same cable as telegraphs were so fundamentally difficult tha they were still only partially-solved in 1920.[22]

2. 4. **Summary of the trunk telephone cable position in the early 1900s.** Let us leave the summin up of the position in 1905 to John Gavey, Engineer-in-Chief of the Post Office:[23]

> In laying out and adding to a system of telephone trunk communication, the extended use, either of small gauge conductors or of underground work generally, is absolutely inadmissible.

3. INDUCTIVE LOADING

The first breakthrough in the use of cables for long-distance telephone communication cam with the application of the technique of inductive loading. A short general history of this topi has been given by Frank Scowen,[24] and a fuller discussion of the process and priorities of i invention by Brittain;[25] consequently we shall here give only brief attention to the origins of th system and proceed as quickly as possible to the early applications in the U.K.

3. 1. **Oliver Heaviside and Silvanus P. Thompson.** I have described in a previous paper[26] th position of theoretical knowledge of telephone transmission around 1890, and shown how it wa Oliver Heaviside who first set out the requirements for distortionless transmission and explained th to achieve them it would be necessary to increase the inductance of the telephone line. At th time distortion due to the greater attenuation of the higher frequencies in the speech spectru relative to that of the lower frequencies was more of an obstacle to long-distance telephony o cables than the actual loss of volume. Heaviside pointed out that distortion could alternatively b reduced by increasing the leakance of the line, but that this would be useless because the loss o volume would be serious. He suggested various ways of increasing the inductance, including th insertion of inductance coils in the line at intervals, but he did not pursue the matter further. I general, telephone engineers at that time were not able to understand Heaviside's difficult mather

atical working, and only one or two, such as S.P. Thompson in Britain, and John S. Stone in the U.S.A., followed up the ideas. Nothing practical appears to have been done in the matter, however, until 1899, when Pupin and Campbell came on the scene.

3. 2. **Pupin and Campbell.** Michael I. Pupin was an immigrant American who had studied mathematics not only in the U.S.A., but as a postgraduate at Cambridge, England, and Berlin. By 1899 he had been in the Electrical Engineering Department at Columbia University for ten years, teaching and researching on a variety of topics. What stimulated his interest in transmission problems and the application of loading coils in telephony is not clear, but after some experiments he filed a patent on loading coils in December 1899 and published a paper giving his theory early in 1900.[27]

George A. Campbell, also American, was an engineer at the Boston laboratory of the Bell Telephone Company who had also studied advanced mathematics in Europe. He was in 1899 assigned the task of extending Stone's work on high-inductance cable, and worked out the basic theory of transmission lines with discrete inductance coils, ascertaining the necessary spacing of coils required to permit distortionless transmission up to a specified frequency. He also made, in September 1899, practical trials over a real cable circuit some 40 miles long, and demonstrated the application of the theory and the fact that the length of cable which could be used for a given quality of transmission was about doubled by loading. His patent was curiously delayed within the Bell organisation and was not filed until March 1900. His first external publication, dated 7 June 1901, was not actually published until 1903.[28]

After an interference action, the official patent priority was given to Pupin, but as the Bell organisation had already acquired his patent for S200,000, and thus held both the competing patents, there was a complete Bell monopoly on loading until the expiry of the patents.

There is no doubt that it was Campbell's formulae and graphs which were used for the design of loaded telephone lines. Although the initial demonstrations had been made on cable circuits, and it was eventually on cable systems that loading had its biggest impact, the early applications were to open wires. The improvement effected was much smaller than on cable, but in the early 1900s all long-distance lines were of open wires and any extension of their range was, in countries like the U.S.A. and some in Europe, very important. The first commercial loaded cable route was that between New York and Newark, New Jersey, (about 20 miles), completed in August 1902; loading enabled a cable of 19-gauge wires to be used in place of the previously planned 13-gauge wires. Others followed rapidly, e.g. New York - Philadelphia (nearly 100 miles) in 1906, and by the end of 1907 the American network had about 86,000 miles of loaded cable circuit, using about 60,000 loading coils.[29] There were several very early papers published showing the results obtained with loading,[30] including some from Germany[31] where very great improvements were claimed, up to five times the length of cable for equal speech loudness.

3. 3. **Loaded cables in Britain, 1901-1910.** In Britain the rights in the Pupin patent were held at first by Siemens Bros., later on by Western Electric. Details of the relationship established have not yet been found.[32] It is certain that the Post Office engineers conducted their own experiments on loading. Sir Gordon Radley said in 1950 that the first experiments were made in 1901 and that in 1902 a complete circuit in the London-Birmingham cable was loaded.[33] I have not found the records of these experiments, but Radley's statement seems to be supported by remarks made by Gavey in 1907;[34] certainly the E. in C. reported in 1903 that it had been found that:[35]

> by adding coils possessing high self-induction at regular intervals of a mile or upwards on underground wires intended for telephonic use, the length over which satisfactory speech can be maintained has been practically doubled.

The following year he reported that two cables, Liverpool-Warrington (about 15 miles) and Liverpool-St. Helens (about 10 miles), had been fitted with coils, and that:

> the efficiency of the treated to the untreated cables has been raised in the ratio of approximately 2.75 to 1.

There were some technical difficulties (as there were in many subsequent years), but the slowness of progress was blamed on lack of funds. The extension of loading was indeed slow: some lines between Manchester and Warrington (about 18 miles) in 1904; Birmingham-Wolverhampton (14 miles) and Cardiff-Newport (about 12 miles) in 1906.[36]

In all these early applications the loading coils were 'air-cored', i.e. there was no iro core. In 1905 the E. in C. reported that:[37]

> Special efforts have been directed during the past year to the improvement of inductance coils for telephone lines. Investigations are at present being made into the electrical qualities of a number of different samples of thin iron sheet obtained from various sources of supply – in some instances specially manufactured for these experiments – with a view to ascertaining what improvements can be effected in the electrical efficiency of these coils.

Publicly he stated:[38]

> the use of iron in any portion of the coils has been found to be deleterious as compared with coils without iron cores. True, the volume of sound was always materially raised where iron was used, but at the cost of articulation, whilst a judicious addition of self-induction without iron always improved both the volume and the articulation.

He went on to say that better progress had been made in America and in Germany, and that i Britain, loading of open lines had been found unsatisfactory.

Iron laminations were, of course, already in general use for alternators and transforme in power systems, but they had to operate only at low power-supply frequencies. The problei of getting low loss at speech frequencies was a new one. However, by 1908 the development c iron-cored coils had reached the stage when the Western Electric design using an iron core wa clearly demonstrated to be superior to the air-core coil, having a better ratio of inductance t resistance without the introduction of any undesirable effects.[39] Henceforth, all loading coi in Britain were iron-cored. A detailed discussion of the technicalities of later loading coil desig is given by Sir Gordon Radley in the paper already cited.

Progress in the application of loading in Britain continued to be slow, but one achievement worth recording. In 1910 a new telephone cable from England to France was laid, using co loading, and the two new telephone circuits showed by subjective measurement a 3 : 1 improvemer in the attenuation constant, due to loading, over the 20 nautical miles of the submarine cable.[4 In modern terms this amounted to a reduction of about 6 dB in the overall loss.

3. 4. The telephone cable expansion, 1912-16. The growing problems of providing for ever-expan ing long-distance telephone traffic on overburdened pole routes, coupled with the progress made the design of cables and loading coils led in 1912 to a decision to commence a comparativel ambitious programme of provision of loaded underground telephone cables, and several cable scheme were authorised for an immediate start, although not without arguments with the Treasury.[41] It ha already been decided to use separate cables for telephony and telegraphy.[42] It is believed that th last combined cable was the Leeds-Hull cable brought into service in 1913. In 1914 it was reporte that schemes involving the use of 18,500 loading coils had been prepared[43] – a large numbe by previous standards in Britain, but less than one-third of the number in use in the U.S.A in 1907. The programme for 1913-14 was for new loaded cables as follows:[44]

London-Birmingham	110 miles.
Birmingham-Liverpool	91 miles.
Cardiff-Swansea	45 miles.
Sheffield-Barnsley	14 miles.
London-Brighton	53 miles.
Glasgow-Edinburgh	45 miles.
Birmingham-Coventry	18 miles.

and some others were added later.[45] Although the Western Electric Company had requeste preferential treatment in regard to the placing of contracts, several companies were actually involve The coming of the First World War in 1914 delayed the completion of some of the cables, but b 1916 the London-Birmingham-Liverpool, the Birmingham-Sheffield, and the London-Brighto schemes were completed[46]. The situation at 31 March 1917 is shown in the map of Fig.1.[4

The London-Birmingham-Liverpool cable had a cross-section as shown in Fig.2. Withi an overall diameter of three inches it contained 4 wires of 300 lb/mile, 28 of 200 lb/mile, 2 of 150 lb/mile and 48 of 100 lb/mile; 104 wires in all which gave 52 metallic-loop circuits an 26 additional 'superposed' or 'phantom' circuits (see Section 4 below). The wires were laid i 'multiple-twin' formation, i.e. two twisted pairs twisted together, which had been found in practice t be the best arrangement for minimising interference when superposed circuits were to be use (The alternative arrangement was the 'star-quad' type cable, described in Section 2.3.) The loadir

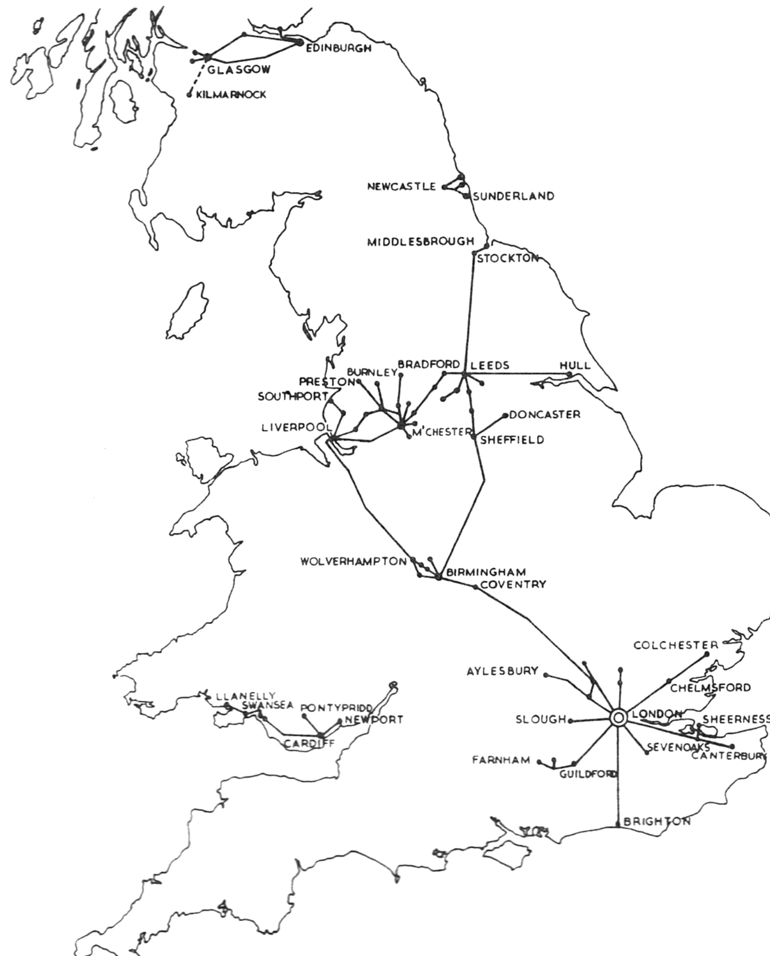

Fig. 1. Main underground telephone cable routes in 1917.

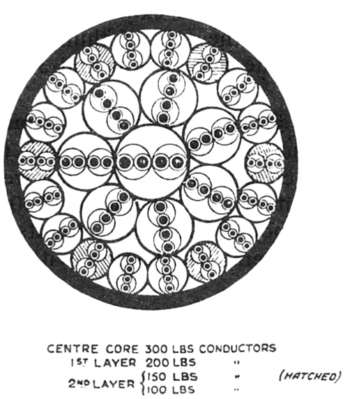

Fig. 2. Cross-section of the London Birmingham-Liverpool cable of 1915.

coils for the normal circuits were of 135 mH inductance spaced at 2.5 miles. This gave an attenuation at a frequency of 800 Hz of 0.0355 dB/Mile, i.e. 7.1 dB from London to Liverpool, on the 300 lb/mile conductors, and rather more than twice this on the 150 lb/mile conductors. Crosstalk between circuits was found to be negligible (of the order of 80 dB below source level on the normal circuits and 67 dB on the superposed circuits) due to the high degree of electrical balance attained in the cable.

Cable transmission technique had now gone as far as it could in the pre-electronic era. For a given gauge of wire, a loaded cable had approximately the same transmission efficiency as an open line.[48] During the period these cables were being laid, the electronic, i.e. thermionic-valve, amplifier was being developed, and after the war it speedily revolutionised telephone transmission. But before discussing this further, we must first explain the idea of superposed circuits, mentioned above.

4. SUPERPOSED OR PHANTOM CIRCUITS

Reference was made above to the use of superposed or phantom circuits. The more imaginative term 'phantom' eventually became generally adopted and it will be convenient henceforth to use only this term even when referring to a period before it was introduced. The idea was to obtain extra circuits by using the two wires of each ordinary metallic loop (which became known as a 'side circuit') additionally as a single conductor comprising the two wires in parallel. This could be done by means of transformers as shown in Fig.3. Thus from four wires, three speech circuits could be obtained. It was, in principle, possible to extend the system to form phantoms of phantoms ('super-phantoms') as also shown in the diagram; this was used in special cases, but not widely, as it was difficult to get the circuits adequately balanced. Balance was indeed the problem of phantom working. If the electrical characteristics of all the wires involved in a phantom system are not identical, then there will be crosstalk between the various circuits. The transformers too must be balanced with respect to the centre-point tappings. It should be noted that balance is a requirement for absence of crosstalk between side circuits even when there is no phantom and it was mentioned in Section 2.3 that a system of selective crossing of wires at joints to cancel out some of the unbalances unavoidably introduced during manufacture was experimented with on the first London-Birmingham cable in 1899. Phantom working introduced more severe requirements and so did the use of loading coils, because these too had to be balanced. It was possible, and indeed normal practice by 1914, to load the phantom circuits by the insertion of suitably-wound coupled coils in the side circuits. The technicalities of the whole matter of balance and phantom working are too great to discuss further here, but they are adequately described elsewhere.[49]

The economic attraction of phantom working is obvious. Not only was the traffic capacity of a given open-wire route or cable increased by 50 per cent or more, but on long lines the transmission loss of the phantom was less than that of the side circuits. The proviso 'on long lines' is necessary, because the transformers which had to be inserted in order to form the phantom circuits added some loss, and on short lines this could exceed the reduction of loss on the line itself. For example, in 1908 the Post Office used the rule of thumb that phantom working added 6 miles of standard cable (i.e. about 6 dB) to the side circuits and 3 m.s.c. to the phantom.[50] Transformers were not at that time very efficient.

The principles of the phantom circuit were invented around 1880,[51] but not used on any significant scale until around 1900 because of the lack of suitable transformers. In the U.S.A. they were then used extensively on open-wire circuits, some of which were hundreds of miles long, and they were used on short open lines in Britain, there being in 1900 a total of 77 phantom circuits used by the Post Office out of a total of about 1000 trunk circuits; this number had increased to 236 by 1911.[52] There was, however, no general satisfaction with phantom working in Britain during this period:[53]

> Superposed circuits on long overhead lines are not found to be satisfactory in England owing to difficulties in maintaining an electric balance of the four wires making up the superposed group, especially in winter weather. Extraneous sources of disturbance on such circuits are also much more difficult to eliminate than on ordinary direct telephone loops.

There is evidence that phantom working on cables had been used before 1908 as Tremain appears to speak from experience of it.[54] However, it was when the new loaded cables came into use just before and during the First World War that phantom circuits came into their own. The

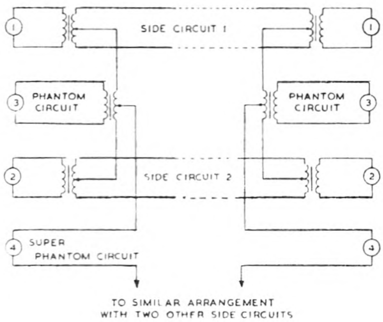

Fig. 3. Arrangement of two pairs of conductors to give two side circuits and one phantom circuit; or four pairs to give four side circuits, two phantom circuits and one super-phantom circuit.

electrical characteristics of the cable were not appreciably affected by weather or season, balancing techniques had been perfected, the loading coils were efficient and stable, and much better transformers were available. Thereafter, until the demise of loaded cables in the late 1930s, phantom working on trunk cables was normal practice.

5. THE IMPACT OF ELECTRONICS ON THE TELEPHONE TRUNK NETWORK

5. 1. **A new concept of telephone transmission.** While the cable developments described above made possible a considerable increase in trunk traffic by enabling more circuits to be provided than open wire routes could reasonably cope with, and also gave increased reliability, yet they in no way permitted any extension of distance. The largest practicable cable was just under 3 inches in diameter and could contain copper conductors totalling about 6.7 tons/mile. The number of conductors evidently depended on the grade of transmission to be provided. It was generally accepted that the limit of loss over a complete trunk connection (i.e. possibly over several links in series, including the shorter local trunks or 'junctions') was 30 dB (to use the modern unit in place of the mile of standard cable then used). This meant that no individual trunk line should exceed 12 dB if it were to be used for through-switching; for lines confined to use between major conurbations 18 dB was allowed. On this basis, one cable could provide 76 wires between London and Liverpool for through switching or 100 wires for 'direct service'. The Post Office wished to extend the cable system to Glasgow, but even for direct service a cable could provide only 48 wires and the cost was prohibitive. Although multiple ducts had been laid on the cable routes already provided, these were becoming full, and it was clear that additional ducts would be necessary if the increase in traffic were to be dealt with by existing techniques.[55]

As far as distance of communication was concerned, the U.S.A. naturally had much more severe problems than Britain. Using phantoms on loaded open wires of enormous size, about 1200 lb/mile, the A.T.& T.Co. had managed to provide commercial speech between New York and Denver (about 2100 miles) in 1910, but this was the limit. Thus the position had arisen that, even with the lowest possible criterion of transmission, i.e. that conversation should be *just* practicable between subscribers, long-distance telephony was now at its limit of distance and unable to cope with the increasing traffic demand. It was in this situation that the thermionic valve came to provide a complete solution. The use of electronic amplifiers or repeaters, using valves, completely revolutionised long-distance telephony. Instead of accepting marginal communication over heavy-gauge wires, telephone authorities could now, in principle (and before long in practice too), provide excellent communication over almost unlimited distances using only light-gauge wires. This was a profound change indeed; but it is only fair to add, in passing, that telephone repeaters had been made, and to a limited extent used in the U.S.A., before the thermionic valve came into use. They were mostly based on the exploitation of the amplifying properties of the carbon microphone, using something like a receiver/microphone combination; H.E. Shreeve designed such a repeater in 1903 and it was used for a short time on the first trans-continental telephone line between New York and San Francisco in 1915. The new electronic repeater, available in that year, quickly displaced it, however.[56] From 1915 electronics ruled long-distance telephony.[57]

5. 2. **British plans to exploit the telephone repeater.** The Post Office had started experimenting with valve amplifiers in 1913, so that by the end of the War in 1918 they had acquired useful experience in the use of such devices. In the planning of the immediate post-war development of the trunk network, full advantage was taken of the new possibilities. It had been intended, before the war, to follow the London-Liverpool cable with another from London to Manchester, forking at Derby to provide a branch to Leeds. This plan was now revived, but on the basis of wires of only 40 lb/mile, so that the cable could contain 320 wires and provide 240 circuits including phantoms. Repeaters were to be provided at Northampton and Derby, each giving a gain (or amplification) of 14 dB; in the event the first repeater station was established at Fenny Stratford and not at Northampton. The total annual cost per circuit was estimated to be only one-third of what it would have been without repeaters.[58]

Progress in implementing this and numerous other similar schemes was very rapid. By March 1920, nine repeater stations had been established (although some of them were only temporary pending the completion of purpose-built stations) on routes to the north, west, and south-east of London; many more were in hand.[59] By 31 March 1923, the repeatered telephone routes were as shown in Fig.4.[60] By about 1930 the original London-Liverpool cable of 1915 had been

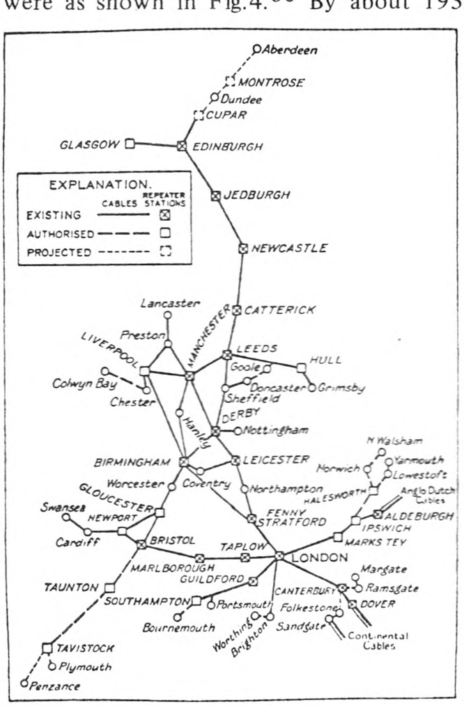

Fig. 4. Repeatered underground telephone routes in Britain in 1923.

pulled out and replaced by a new cable with 704 wires of only 25 lb/mile.[61] From 1923 to 1930 the mileage of telephone trunk lines more than doubled; this rate of increase was, however, rather less than in the U.S.A., which had about ten times the mileage anyway.[62]

The new cables were loaded with a new type of loading coil developed by the Western Electric Company, using cores made from iron dust instead of iron wire. These had better characteristics than the older ones, but left the Company with a monopoly of coil supply. The amplifiers, however, were not subject to monopoly control. The Post Office had managed to get G.E.C. to design and manufacture suitable repeaters, and in 1921 the E. in C. of the Post Office reported gleefully that the Western Electric Company would not be able to establish the monopoly on repeaters that they had done in other branches of telephone engineering.[63] Further discussion of this matter will be given later.

5. 3. **The telephone repeater itself.** There were basically two types of repeater system:

(a) those which provided both-way amplification on a single pair of wires (see Figs. 5 and 6) – the 'two-wire repeater', and

(b) those which used two pairs of wires, one for one direction of transmission ('Go' direction, say) and the other for the reverse direction ('Return' direction); each pair had only uni-directional amplifiers (see Fig. 7) – the 'four-wire system'.

Obviously type (b) required twice the number of wires and was therefore much more expensive. It was not used at first for this reason. However, both-way amplification involved many very difficult problems, and it was almost impossible to provide as much amplification as could be provided on the four-wire system. For many years the two types co-existed, but eventually the four-wire system dominated.

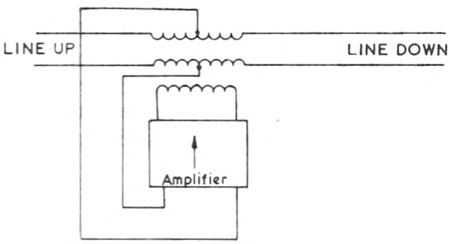

Fig. 5. Single type two-wire repeater.

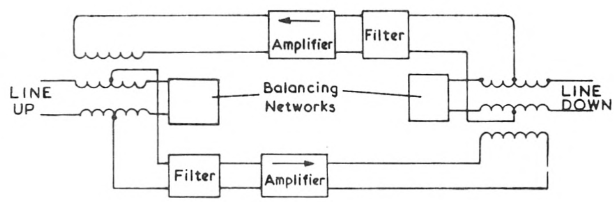

Fig. 6. Double type two-wire repeater.

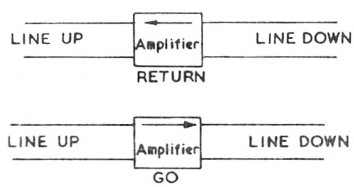

Fig. 7. Four-wire repeater.

The technicalities of telephone repeaters cannot be very adequately discussed here,[64] and only the critical problems will be taken further. The chief of these was the prevention of instability, 'singing', or self-oscillation of the amplifier system. Taking first the both-way or two-wire repeater, this had two forms, as shown in Figs. 5 and 6. In the single type, only one amplifier was used, coupled to the lines by means of a differential transformer as shown. It will be observed that the output of the amplifier is coupled to the same transformer as the input. Singing, or self-oscillation, will obviously be liable to take place unless (a) the transformer is accurately symmetrical and properly connected, and (b) the impedances of the 'Up' and 'Down' lines are identical at all frequencies at which amplification is effective. The more these conditions are departed from, the less amplification can be provided without singing. Reasonable balance of the transformer was not too difficult to achieve, but identical line impedances could be attained only if the lines were identical on both sides; this meant that the repeater must be inserted at the exact half-way point of the section of line, exactly half-way between loading coils, and that there must be no irregularity in the lines, and the terminating impedances at the far ends must be the same. Evidently this was impossible to achieve in practice, so that single-type two-wire repeaters could be operated only with quite low amplification. They were quickly displaced by the double type shown in Fig.6. In this system there was no need for the lines to be identical; each one was separately balanced by an artificial network of inductors, capacitors and resistors, carefully adjusted to match the line impedance with as much accuracy as the irregularity of the frequency response of the latter allowed.

This system allowed much more amplification to be used, and just before the final demise of the two-wire repeater on main routes in about 1935, it was found possible to operate two-wire trunk lines up to about 200 miles in length with no overall transmission loss between the terminal stations – i.e. with amplification equalling the loss of the line and transformers.[65]

The need to maintain a relatively accurate balance of impedances made it difficult to operate two-wire repeatered lines at the level of overall transmission efficiency that soon became the aim. An overall loss of only 3 dB for main trunk lines became the basis of planning before 1930, and by 1933 zero-loss was the accepted aim.[66] These standards could be much more easily and consistently maintained with four-wire repeaters, and since conductors of only 20 lb/mile could now be used, the cost of providing four-wire circuits was not prohibitive. Thus the four-wire system, which had been used on some routes since the early 1920s, became standard in the early 1930s.

On these low-loss circuits, problems arose from echoes. Although the overall circuit was stable, nevertheless there was sufficient backward transmission for a speaker's voice to be reflected back down the line at a quite audible level. Since on the long routes the time of transmission was considerable, these 'echoes' were significantly delayed, perhaps by 100-150 msec, and so interfered with the speaker's efforts to speak quickly and clearly. Thus 'echo-suppressors' had to be fitted on long routes; they were devices which used the speech power in one direction to suppress temporarily the amplification in the other.[67]

Another matter worth mentioning is that in repeatered systems it was usual to insert electrical networks in the repeaters to correct the frequency-response of the system, so that the overall system had approximately the same transmission efficiency at all frequencies within the specified audio band. These networks were called 'equalisers'. The use of repeaters made the crosstalk requirements of cables much more severe because of the greater differences of signal level, and so better balancing techniques were necessary.

5. 4. Four-wire circuits and Western Electric patents. Having outlined some principles and their applications above, it will now be possible to describe how four-wire circuits were converted to two wires at the ends and how the Post Office was able to prevent Western Electric from obtaining a monopoly in repeater systems. The negotiations in this matter took place between 1920 and 1922.

The Western Electric Company held a patent by J. van Kesteren[68] which covered a four-wire repeater system substantially as in Fig.7 and with the GO and RETURN lines joined in parallel at the end of the line as in Fig.8(a) in order to make connection with the local telephone network, T. (The company also held some patents relevant to two-wire working,[69] but these were not in the class of master patents and could be circumvented). When the Post Office decided in 1920 to have an experimental four-wire repeatered system between London and Portsmouth, with repeaters at Guildford, Western Electric tendered at £60,600 (to include 60 two-wire and four-wire repeaters) with a claim that their holding of the van Kesteren patent prevented the Post Office from awarding a contract to any other firm.

The Post Office engineers had themselves designed a four-wire terminating system of the type shown in Fig.8(b). This used a differential transformer with a resistance R_1 to give an approximate match of impedance to the local line T. This system effected a good measure of decoupling between GO and RETURN and enabled the circuit to work, if necessary, at an overall gain rather than loss. It was thus claimed by the Post Office that the van Kesteren patent was ineffective.[70] Since the Post Office also estimated the cost of the proposed installation at only £35,000, Counsel's opinion was sought as to the patent position. The Counsel concerned were the Attorney-General and J. Whitehead, K.C., and they upheld the Post Office view. Confronted with this, W.E. reduced their tender to £54,000, but

> This being still £19,000 in excess of the [Engineering] Department's estimate for installing its own system, a case was stated to the Secretary on 9 April [1921] for rejecting the Company's tender and proceeding with arrangements for installing the Department's system.

Thus was Western Electric's stranglehold broken. The terminating arrangement shown in Fig.8(b) became standard, with the later addition of the device on the right (enclosed in dashed lines) which connected a resistance R_2 to match R_1, so as to keep the system stable when no local line was connected.

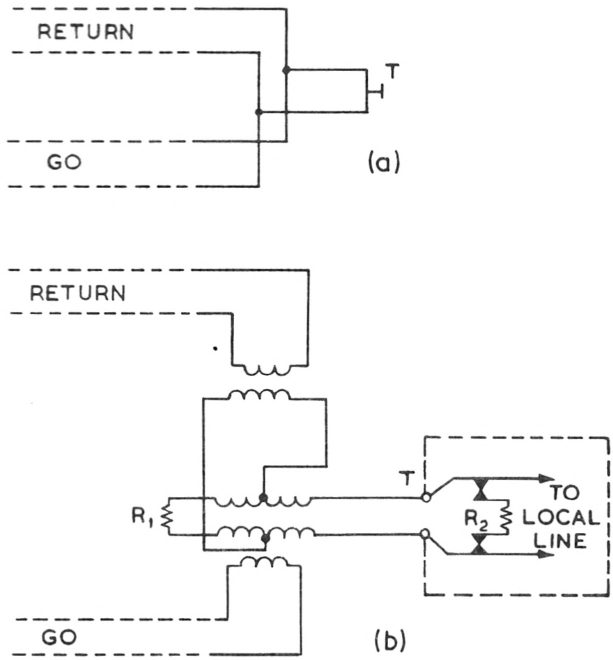

Fig. 8. Terminal arrangements for four-wire circuit.
(a) Van Kesteren system of 1913.
(b) Post Office system.

5. 5. **Repeater stations.** To house the large number of repeaters required on the projected new routes, special repeater stations were built in most cases. These were usually rather plain, typically utilitarian, Office of Works brick buildings on two floors. The repeaters and associated equipment were on the first floor, and the power plant on the ground floor.

Repeaters were mounted on panels which were screwed on to vertical racks. Their power requirements were 15 volts for the filament supply (two valve filaments in series in each repeater), 150 volts for the high-tension supply, and 20 volts for the grid bias. About 20 W was required altogether for each pair of valves. Batteries were provided, with charging by engine-generator sets. These used horizontal slow-speed 4-stroke Diesel engines such as the Ruston & Hornsby Cold Starting Engine Mark 11H, which was of 76 b.h.p. For a long time the public electricity supply mains were not used, as they were considered to be insufficiently reliable. In the more isolated places, a residence for one of the maintenance men was incorporated in the building.[71]

6. NEGATIVE FEEDBACK AND THE END OF AN ERA

The further development of the systems described above came virtually to an end around 1935. By that time negative feedback had come into the engineer's repertoire. Although invented by H.S. Black (in the U.S.A.) in 1927, the principle and applications of negative feedback were not published until 1934.[72] The important thing about this principle in our context is that it made possible the design of amplifiers of such quality that it became practicable to transmit several speech channels, translated to different frequency bands (what became called a 'frequency-division-multiplex' system) through the same amplifier without mutual interference.

Systems in which speech channels were translated to different frequency bands and then transmitted simultaneously on the same circuit were generally called 'carrier' systems, and this principle had been known since at least the early 1890s.[73] It had been, for some 20 years, applied on a limited scale to open-wire lines where there were no amplifiers to cause trouble, and on an even more limited scale but without much success to repeatered cable systems on the basis of a single 'carrier' channel in addition to the direct audio. Now, however, it became possible to have 12, 24, or hundreds of channels on the same circuit.

To achieve the wide frequency band needed for such a system, new cables were laid without loading coils, and old cables were 'deloaded'. The explosive expansion of trunk telephone traffic which has led to the trunk routes of today having thousands of channels for every one provided in the 1920s, could not have come about without a new system, and the carrier or frequency-division-multiplex system has persisted till today. 1934 indeed marked the beginning of the new era and the end of the old.

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DISCUSSION.

Mr. K. Geddes remarked that he believed the 1899 London-Birmingham cable did carry trunk telephone circuits. **Prof. D.G. Tucker** was interested to hear this. **Mr. F. Scowen** said that in about 1936 the Post Office Research Department made measurements with a view to using the cable for a 16 kHz carrier system; he could not remember whether the proposals were adopted. **Prof. Tucker** said that that cable was the first in Britain on which selective jointing was used to reduce crosstalk between the pairs.

Mr. E.T.C. Harris asked for more information about the receiver/microphone repeater; he also asked why there was the delay between the invention of the negative feedback amplifier and its first application. **Prof. Tucker** said that the Shreeve amplifier had been used to a limited extent but it was not a very satisfactory device. The thermionic vacuum tube (valve) amplifier produced far less distortion and the use of such amplifiers did not noticeably degrade the quality.

A visitor asked how the gauge of the wires on overhead lines was decided? **Prof. Tucker** replied that the choice was made to give a suitable transmission loss over the route being planned. Originally this was done on an empirical basis but in the early days of this century methods of measuring the loss were developed. At first these were subjective; the transmission over the line (looped back at the far end) was compared with that over an adjustable artificial line of standardized construction. The theory of transmission was gradually built up as shown, for example, in the many articles which appeared in the Post Office Electrical Engineers' Journal in the early decades of this century. The first methods were later replaced by single tone measurements and the use of instruments to make the comparisons, instead of the earlier subjective testing. By the time of the introduction of the loaded cable it had become a routine matter to predict the transmission performance of a particular cable.

A visitor asked whether the phasing of the phantom circuit was important. **Prof. Tucker** replied that the centre point of the transformer winding had to be exactly placed and this was effected by using a pair of wires to wind both halves of the winding together, this was called bifilar winding. Any unbalance in the electrical position of the central point would produce cross-talk from side circuit to phantom circuit and vice versa.

Lord Wilson said that he had been impressed by the overhead lines over Shap Fell. They were supported by single cross-arms on poles. Was this to reduce the possibility of faults being caused by snow accumulation? Overhead wires are now rarely seen; is this to save copper or maintenance? **Prof. Tucker** said that he had no information about the present economic comparisons between overhead and underground distribution. It is now the practice to use two wires in a plastic cover for circuits connecting a subscriber to an underground cable leading to an exchange; such overhead distribution is mainly used in rural areas. Underground circuits are much cheaper for maintenance. **Prof. Tucker** added that before the Second World War a few overhead trunk circuits remained in use. **Prof. A.W. Skempton** remarked that he had seen no early illustrations of overhead wires in London comparable to the forest of wires that were apparent in New York according to the slide shown by Prof. Tucker (not included in the paper). **Mr. Geddes** said that he had come across the same difficulty. It was probably because the overhead distribution to subscribers was made via roof-top distribution poles. F.G.C. Baldwin refers in his book "The History of the Telephone in the United Kingdom", Chapman & Hall, 1925, to 'the unknown world of the roof-tops'.

Mr. J.W. Butler spoke of the progress in metallurgical theory and practice; was there any stage when there were delays because of the lack of such progress? In the development of dust cores, both pressed and sintered, the Post Office and its contractors must have made very big contributions to metallurgy. Turning to cables, did the Post Office and its contractors use any special paper and were new papers developed. What happened when cables were recovered; was any attempt made to recover the copper and lead? **Prof. Tucker** replied that overhead telegraph circuits first used galvanised iron wires. These were unsatisfactory for speech signals because the resistance of an iron conductor rises rapidly as the frequency increases (skin-effect) and this has the effect of increasing the loss of the higher speech frequencies. Copper, which is a much better conductor than than iron, experiences this skin-effect to a much smaller degree, but its mechanical strength is much less. On the continent the telephone engineers carried out experiments with silicon and phosphor-bronze conductors; the first Paris-Brussels international circuit in the mid-1880s used silicon-bronze conductors but even these came down in storms. In Britain hard drawn copper was used and this and similar solutions were investigated by metallurgical R. & D. projects. As far as **Prof. Tucker** knew, the Post Office had no metallurgical department before about 1930. In America, they had used from the 1880s, a steel-cored wire for overhead telephone conductors, the steel core having a diameter of 3mm with a 1½mm cover of copper. **Prof. Tucker** went on to say that Sir Gordon Radley had read a most useful historical paper on loading coils and other problems to the Institution of Electrical Engineers during the Heaviside Centenary Proceedings of 1950 and serious students should read that published paper. Manilla paper had been used from the beginning but Prof. Tucker was not aware of any special research on this. The paper was at first impregnated with paraffin wax but this was soon omitted; the insulation of the conductors relied on dry air and the paper was there only to provide for the mechanical separation of the wires. Regarding the query about scrap cable, the copper and lead were certainly recovered and reprocessed.

Dr. Darling remarked that one big difference between open wires and cables would be in their temperature variation through the seasons. Did this have a bearing on the advantages in using underground cables? **Prof. Tucker** replied that this was so and one of the effects was the greater constancy in the cable's characteristics which led to smaller variations in the cable balances that affected phantom working and later the operation of the two-wire repeaters. On long routes in the U.S.A., the compensation circuits had to be provided to allow for temperature changes and this was particularly necessary on overhead cable routes.

Mr. Scowen remarked that it was important to be able to identify the wires of a quad for repair purposes and this was done by printing one, two, three and four narrow bands across the manilla papers. The spacings between the marks were so arranged that the same number of bands were printed on each short length (about 2 inches) of the paper.

Prof. Tucker gave a somewhat simplified explanation of crosstalk balancing and remarked that a crosstalk ratio of 80dB (i.e., a power ratio of a hundred million to one) was regularly achieved. **Mr. Geddes** expressed surprise at this figure; he thought that 40dB would be adequate. **Prof. Tucker** said that for intelligible crosstalk, such a figure as 40dB would be quite unacceptable. It was quite practicable to carry on conversations over a circuit of 50dB loss. At the time of the First World War, the over all loss accepted for a complete trunk connection was 30dB.

Mr. Torsten Berg said that his telephone was connected to the exchange via an underground cable but in wet weather conditions this frequently went faulty. **Prof. Tucker** replied that this was probably because of a pinhole in the sheath and **Mr. E.T.C. Harris** said that this is now largely obviated by maintaining a positive pressure inside the cable.

The vote of thanks was proposed by **Dr. Brian Bowers** and this was passed with acclamation.

CORRESPONDENCE.

Mr. F. Scowen wrote: In March of 1916 there was a great storm in this country which severed all overhead lines between London and the North, leaving the London-Birmingham-Liverpool underground cable which had been completed only a fortnight before as the only line of communication. In order to restore communication to Ireland the Post Office Research staff installed two repeaters in Liverpool between the cable pairs and the extensions to Dublin followed in May of the same year by the installation of four repeaters at Birmingham.

The following comparison of the metallic parts of trunk circuits is of interest:

TYPE OF CIRCUIT	DATE	WEIGHT IN TONS PER CIRCUIT PER 100 MILES	
		Copper	*Lead*
Overhead, 600lb/mile	1896	56	-
150lb/mile cable with phantom circuits	1914	9.3	17.1
40 lb/mile cable with 2 wire repeaters	1922	3.7	8.4
20 lb/mile cable with 4 wire repeaters	1926	3.7	4.9

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