WS No. 19 Mark III

THE OPERATION OF SINGLE- AND MULTI-CHANNEL TELEPRINTER SYSTEMS OVER RADIO LINKS

Notes: 1. This information is provisional and is supplied for guidance pending the issue of more complete instructions. All errors of a technical nature should be notified in accordance with Tels. A 009.

2. This E.M.E.R. is based on a Ministry of Supply monograph written by Dr. E. V. D. Glazier.

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Distribution—Class 800. Codes Nos. 4 and 5

GENERAL

1. In Great Britain and most other countries the system of inland telegraphy, which operates mostly over land lines, was converted during the ten years prior to the Second Great War to 5-unit code working, using teleprinters. The advantages claimed for this system are, briefly, that messages may be sent from a keyboard to provide immediately a tape or page-printed copy at the distant point. The use of a code of constant length has permitted the teleprinter to be developed into a compact, efficient instrument. A further advantage of the system is that circuits may be switched through and messages sent from any teleprinter to any other teleprinter in the network. The systems used are described in Tels. T 242.

2. Radio telegraphy is now undergoing a similar change, so that ultimately the complete line and radio system will be uniform and inter-working will be possible. This regulation provides an elementary description of the teleprinter and the problems which occur when it is operated over radio links; it does not attempt to describe all known systems in detail.

PRINCIPLES OF TELEPRINTER OPERATION

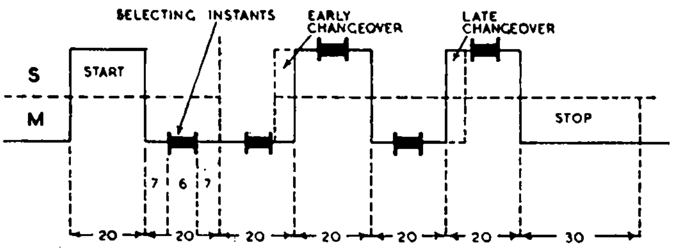
3. A teleprinter is an automatic telegraph instrument, consisting of a transmitting mechanism operated by a keyboard not unlike that of a typewriter, and a receiving mechanism which prints the received signals as letter or figure characters on paper, either page or tape. Depression of a character key causes the transmitting mechanism to send a code of positive and negative electrical impulses into the transmission system, which may be a line or radio link. At the distant end of the link the positive and negative impulses are received by the receiving mechanism which is thereby caused to print the desired character.

4. The type of code signals used is known as the "5-unit code." The signals for each character consist of a positive polarity "start signal" of 20 milliseconds (mS). duration, followed by five positive or negative code signal elements, each element being of 20mS. duration, followed by a negative polarity "stop signal" of 30mS. Thus all characters are of constant duration, namely, 150mS. This is the first important difference between the 5-unit and morse codes. When no signals are being transmitted the teleprinter continues to transmit negative polarity. This has been arbitrarily called the "marking" condition. The positive impulses during signalling are called "spaces." A typical teleprinter signal is shown in Fig. 1(a) and a morse signal in Fig. 1(b).

5. The object of the start signal is to prepare the distant teleprinter for the reception of the five units or elements of the character which follow. This start signal causes the receiving mechanism to be coupled to the driving motor for 140mS., after which it is uncoupled until the next start signal is received. This feature removes the necessity for having accurate synchronism between the sending and receiving mechanisms. As long as all the teleprinter motors in a network are within the prescribed speed tolerances of $\pm$ 0.5% complete inter-working is possible. For this reason teleprinters are known as "start-stop" telegraph instruments.

6. The process of setting the receiving mechanism to print the desired character is carried out during a short instant at the middle of each 20mS. code element. These instants are known as "selecting instants" and are shown diagrammatically in Fig. 1(a).

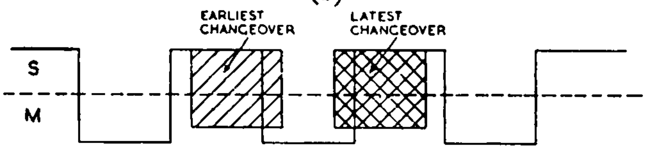
(a)



DISTORTION = $\frac{x}{20}$ x 100 %

5 UNIT CODE LETTER J SHOWING SELECTION INSTANTS & DISTORTION

(b)



T A-172/1-1 MORSE CODE FOR LETTER S SHOWING DISTORTION

Fig. 1—Comparison of teleprinter and morse code signals

Telegraph and teleprinter distortion

7. If the impulses are generated accurately by the sending teleprinter and they are transmitted so that they are faithfully reproduced at the receiving teleprinter, then, provided the latter is in correct adjustment, the desired character will be printed. Transmission systems can, for reasons explained later, produce telegraph distortion at the receiving end of the system; if the change-overs from positive to negative and vice versa do not occur accurately at the 20mS. intervals with respect to the first part of the start signal, then there is telegraph distortion present. In the case of teleprinters the definition of distortion is as follows :—

> The distortion of a received teleprinter signal is the time by which any change-over is early or late with respect to its correct position (as measured from the first instant of the received start signal), expressed as a percentage of the unit signal element length.

8. It will be observed from this definition that if the first change-over of the start signal is early or late with respect to the true starting instant, then all subsequent change-overs are liable to be distorted, even though they may occur at the true instant.

9. In Fig. 1(a) if the change-overs had occurred at the instants shown by dotted lines (x) mS. away from the corrent instant with relation to the start, then the distortion would be $\frac{(x)}{20}$ x 100%

10. Distortion may in general be of three kinds: fortuitous, bias and characteristic. Fortuitous distortion is distortion of a random nature due to some variable feature of the transmission link. Bias distortion may be caused by some asymmetry of the equipment or link. Characteristic distortion is generally a function of the equipment and occurs consistently with any given combination of signal elements.

11. From Fig. 1(a) it will be seen that as long as the intended change-over occurs between two selection instants the correct character will still be printed. It follows that, since the selection instant of a teleprinter is approximately the middle 6mS. of each element, the distortion which a teleprinter will handle is approximately 35%. If change-overs occur outside these tolerances or if spurious change-overs are introduced by the transmission system, then incorrect printing may ensue. However, if a very short spurious pulse is introduced between two selection instants, then it is still possible for the correct character to be printed. Furthermore, very short impulses may have insufficient energy to move the receiving magnet.

12. If the selection instants were reduced so as to be of extremely short duration, it is evident that the theoretical maximum distortion which a teleprinter could handle tends to 50%.

13. By way of comparison, automatic morse equipment (Tels. T 282), which operates on a somewhat different principle, can have a theoretical maximum tending to 100% although in practice the limit is of the order of 70%. Very short spurious pulses of the type described above can cause wrong printing with the morse system, if they should occur so as to split a dash into two dots. In both cases the limit is imposed by the power required to operate the receiving mechanism.

CAUSES OF TELEGRAPH DISTORTION AND MISPRINTING IN RADIO LINKS

14. It is important to know the causes of telegraph distortion and misprinting on radio links, and to take all possible steps to reduce such effects. This is especially true on military radio links which are to carry messages in cypher. An omitted or spurious character at the receiving teleprinter may cause a message to be difficult to decypher.

15. Telegraph distortion can be produced during transmission through a radio link by one or more of the following causes :—

(a) *Noise*
Noise (atmospheric or interference) appearing at various points in the radio link can produce voltages which interfere with the receive relay.

(b) *Fading*
Fading of the radio signal, either slow or rapid, can cause telegraph distortion. If the radio equipment is designed to handle such fades, then, in the limit, during deep fades the noise will cause distortion.

(c) *Transmission time*
Variations of transmission time of the radio signal, due to varying reflection paths (also known as multi-path effects), will cause telegraph distortion.

(d) *Radio equipment*
Various parts of the transmitting and receiving equipment can cause distortion, e.g., oscillators having frequency drifts, relays, filters, etc.

16. In general the causes detailed in sub-paras. 15(a), (b) and (c) will produce fortuitous distortion and that in (d) characteristic distortion. The manner in which some of these features of radio links cause distortion will now be considered. The term distortion will be used somewhat loosely to include true telegraph distortion together with omitted and spurious characters.

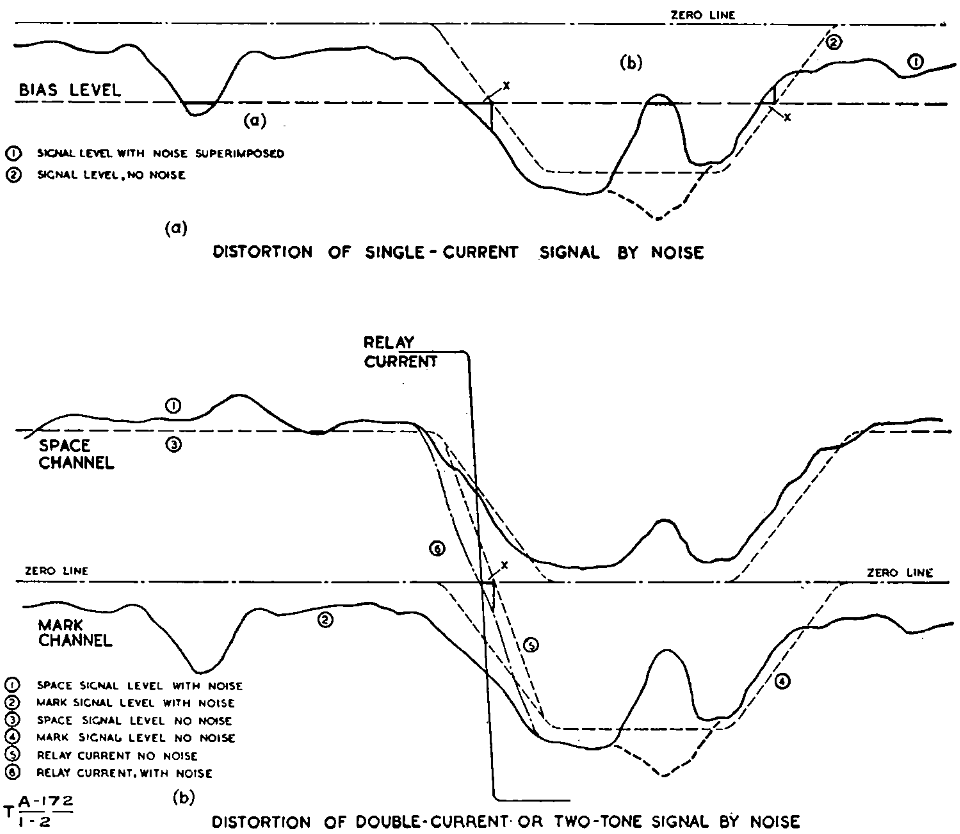


Fig. 2—Distortion due to noise

Distortion due to noise

17. Before actually considering in detail the various radio teleprinter transmission systems, it is desirable to examine in general terms how noise can interfere with teleprinter signals. Consider first of all a simple C.W. system in which a pulse of radio carrier conveys a mark signal; and no carrier a space signal, the receive relay being biased to half the signal strength. Such a pulse envelope received with no noise interference is shown dotted in Fig. 2(a). Suppose the pulse originates at the transmitter with square flanks (although this is not essential), then a very wide band-width would be required at the receiver to preserve the square pulse. Such a wide band-width would admit noise during the space periods and the probability of noise causing misprinting, as at A, would be high. Restriction of band-width at the receiver reduces the probability of this, but at the same time it causes sloping flanks on the received envelope. There is a lower limit to the band-width as will be explained in paras. 108–109. If the receiving system is correctly biased, accurate signals can still be received, even if the envelope is trapezoidal. However, the noise combines with the signal and produces a received signal as shown by the full line. The noise produces distortion as shown by the displacements "x," besides causing possible misprinting as at A and B.

18. In the case of a 2-tone signal in which one tone or carrier represents a mark and another a space, as in Fig. 2(b), similar remarks apply. Noise interference can still cause spurious change-overs and distortion, although it is evident from this diagram that the effect of noise will be reduced.

19. The degree of interference produced by noise will depend upon the character of the noise. In the case of steady random noise the interference will be less severe than with noise due to, say, local lightning. It is necessary to have some definition of signal-to-noise ratio for a quantitative study of this problem. It is usual to define the ratio when it is measured at the output of the filter with the narrowest pass-band in the receiving system. The width of the filter pass-band in cycles per second should be specified and considered when comparing radio links. Noise should be measured with an R.M.S. meter with heavy damping, preferably of the hot-wire type. In practice it will be more convenient to measure signal plus noise, but for most purposes this will approximate to the signal. When the noise is not of the steady type, it may be necessary to consider the peak signal-to-peak noise ratio.

Distortion due to fading

20. Having accepted the principle that the received signal at the narrowest band-width will be trapezoidal in shape, then, from Fig. 2(a), if the signal amplitude varies and the bias level does not, distortion of the element length will occur. Even with the best-known means of controlling the bias point, such distortion is inevitable. The 2-tone system again has advantages in this respect since the receive element (relay or otherwise) is operated unbiased. However, a large disparity between mark and space signal amplitudes will produce distortion in the 2-tone system.

21. Even if all known automatic gain-control devices are used, then, during very deep fades, the signal-to-noise ratio will deteriorate and distortion may be caused by the noise.

Distortion due to multi-path effects

22. On many types of radio link the signal reaching the receiver aerial may have travelled over widely differing paths. Those signals which have suffered many reflections will generally have travelled longer distances and will arrive after signals having the minimum reflections. Thus a particular carrier pulse in the C.W. system will appear at the receiving aerial as the sum of a number of pulses starting at different instants of time, of different amplitudes and with differing sinusoidal phases. The leading edge of the carrier pulse can thus be very erratic. According to some authorities, on links of three or four thousand miles the time between the first arrival of a steep-fronted pulse and its last arrival can be 2 or even 3mS. Similar effects occur with other than C.W. systems. So far as the telegraph equipment is concerned, this erratic build-up of the signal element produces telegraph distortion of the fortuitous type.

Distortion due to equipment

23. Distortion may be caused in the equipment at many points of the circuits, and it is important to keep this kind of distortion at the absolute minimum, so that the fortuitous (which add to the equipment distortion) produce as few errors as possible.

24. Transmitting and receiving relays can cause bias distortion if they are incorrectly adjusted. In the case of double-current signals it is important to see that signals are generated symmetrically. In other respects the transmitting equipment is generally free from distortion.

25. The receiving equipment is somewhat more difficult to deal with, as has already been indicated in para. 20. Imperfections of the automatic gain-control circuits are very difficult to correct, especially with single-current systems. Frequency drifts can cause bias distortion in some systems, as can mistuning of receivers. Careful design of the final teleprinter D.C. signal circuits is essential to avoid distortion.

THE REDUCTION OF MISPRINTING ON RADIO TELEPRINTER SYSTEMS

26. A radio link with a consistently good signal-to-noise ratio, for example, 25db., measured at the output of a 100c/s wide filter, can in general be used for successful radio teleprinter operation, using normal line voice-frequency telegraph practice. Radio links using U.H.F. and some links of the V.H.F. type fall within this class.

27. Radio links of the H.F. type do not always have such a good signal-to-noise ratio and they are subject to fading. Such links form a very important section of communications, and it is therefore necessary to use methods of modulation and other devices to minimize the effect of noise. The methods of modulation developed for greater reliability on the H.F. band are also applicable to V.H.F. and U.H.F. radio links. Consideration of these problems is therefore applicable in large measure to most types of radio channel.

Use of greater transmitter power

28. Signal-to-noise ratio can generally be improved by using greater transmitter power. This is largely a matter of economics, but in the case of mobile or other portable or compact installations the minimum necessary power

should be used in order to avoid interference with the adjacent receiver. This method of improving signal-to-noise ratio should not be used unless other devices fail to achieve the desired result.

Choice of system of modulation

29. Several methods of modulating the radio frequency are available. These will be broadly divided into :—

(1) Direct methods in which the positive and negative teleprinter pulses control the R.F. directly.

(2) Indirect methods in which the pulses are converted into one or more tones which then modulate the R.F. by any one of the several known methods, e.g., A.M. or F.M.

30. Either of these methods may be further sub-divided into single-current working or double-current working. With single-current working one polarity of pulse or one tone frequency is used to transmit a mark and no pulse or tone to indicate a space. This method requires the application of a bias, either electrical or mechanical, at the receiving end to change the relay, or other receiving element, to space on removal of the signal.

31. With double-current working one polarity or one tone frequency represents a mark, and opposite polarity or a different tone frequency represents a space.

32. When comparing the different systems of modulation to determine which provides the best signal-to-noise ratio, it is very convenient to imagine a hypothetical filter of, say, 100c/s width centred on the actual incoming radio frequency which conveys the signals. For example, when the signal is a tone sideband of a radio frequency carrier, the narrow filter may be assumed to be centred on this sideband. In practice the narrow filter must be inserted after one or more stages of frequency changing, but provided these stages are correctly designed, the above assumption is tenable.

Direct methods of modulation

33. There are two types of direct modulation, the single-current and double-current kinds. Both of these methods of direct modulation place somewhat rigid requirements on the transmitter and receiver oscillators. The drift of these oscillators must be held to the very tightest limits. Some form of frequency drift alarm or automatic frequency-control is desirable.

Single-current working

34. In this system the carrier is transmitted at maximum level for a negative polarity or mark, and suppressed for a positive polarity or space. This is also known as continuous wave (C.W.) working or simply " on-off " keying.

35. The idle condition of a teleprinter is transmission of the " mark " or negative polarity. It is necessary for the carrier to be transmitted in this condition in order that the receiver A.G.C. shall be held to the level of the signal. If the reverse condition were used, the receiving teleprinter would operate on noise during the idle condition.

36. The C.W. method of transmission has been very commonly used, especially in conjunction with high-speed morse equipment. It has been used for teleprinter operation but has not always been successful on links operating near the limit of noise.

37. The method of modulation and detection is generally very simple. At the transmitter a relay is usually employed to switch the R.F. on and off at an appropriate stage. At the receiver the principle of detection is simple rectification. This rectification is carried out either at the I.F. or at a beat frequency. In either case the signal is passed through a filter to reduce the effect of noise components at other frequencies. The resulting D.C. from this rectification is caused to operate a polarized relay. A bias must be applied to this relay to enable it to change over when the carrier is removed. Preferably this bias should be automatically set to half the signal current and should vary with it.

38. It will be seen, however, that in conditions of variable noise and rapid fading the setting of the bias is no easy matter. This method is similar to single-current line telegraphy.

Double-current working

39. In this system the carrier is transmitted at maximum level for a negative polarity or mark, and at maximum level but 850c/s lower frequency for a positive polarity or space. This method is known as carrier shift (C.S.) or double-frequency keying, because the radiated carrier is shifted in frequency by 850c/s (or any other suitable amount) to transmit the intelligence.

40. In this method it will be seen that the transmitter works at full power continuously. The advantages of this method will be touched upon briefly. Firstly it will be seen that the receive relay need not be operated in the biased condition. It will thus be less susceptible to variations of signal level and noise. The received signal may be passed through a limiter as in F.M. practice. This has the effect of reducing the disturbance caused by noise, provided the noise is not too large in voltage. The method is similar to double-current line telegraphy. It is also akin to the F.M. method of radio.

Indirect methods of modulation

41. There are three main methods in current use :—

(*a*) Single-tone

(*b*) 2-tone

(*c*) 4- or 6-tone.

Single-tone

42. In this method transmission of negative polarity or mark is effected by sending a tone (usually audible) into the transmission system. For positive polarity or space the tone is suppressed.

43. The tone is used to modulate the R.F., either by amplitude or frequency modulation. In the former case the tone should cause 100% modulation to secure the maximum gain over noise. Even so, it should be noted that the power in one sideband (which is all that is effective in overcoming noise) is only one-quarter of the steady carrier power. In a single-tone system the receiving relay has to be biased to half the amplitude of the signal, and it is therefore analogous to single-current telegraphy.

47. With single-tone working applied to ordinary A.M. or F.M. links, there are no special frequency stability requirements on the radio links. However, it should be noted that where single-tone working is applied to a single sideband radio system the result is analogous to

C.W. transmission, except that with single side-band working there is usually a continuous low-level signal transmitted for frequency and level control purposes.

2-tone

45. In this method a mark is transmitted by sending one tone over the radio system, and a space by sending a different tone. Each of the two tones can be transmitted over the radio system by A.M. or F.M. Each tone should modulate 100% to secure the maximum gain over noise.

46. The relay in this method may be operated unbiased, and the system is thus analogous to double-current working. Frequency stability of the radio equipment is not so important, excepting where the system is single sideband. In the latter case it should be noted that 2-tone transmission over a single sideband system is equivalent to the carrier shift method of working, except that vestigial carrier is usually transmitted for level and frequency control purposes.

47. The 2-tone system has been very widely used, but with A.M. radio links only one-quarter of the steady carrier power is available for discrimination against noise.

4- and 6-tone

48. In the 4-tone system two tones represent a mark and two different tones a space. The 6-tone system is similar, except that there are three mark tones and three space tones. These systems have been used to give greater reliability on radio links subject to selective fading, and are discussed in more detail in para. 91.

49. These systems are applicable to A.M. or single side-band links. In the 4-tone case each tone must modulate the transmitter 50%. This represents a loss of signal strength, but if 4-tone working overcomes selective fading, such a loss must be tolerated, and increased power used if necessary.

50. In the 6-tone case the modulation per tone must be reduced to about 33% unless the tones are phased, when it can be increased to about 45% (see para. 63). This system was widely adopted by the German Army but without phasing of tones.

Comparison of different methods of modulation

51. The various systems of modulation are summarized in Table 1. The last system in this table represents the transmission of tones over single sideband radio links with vestigial carrier for frequency and gain control purposes. This system will be discussed in greater detail in paras. 98-102. These systems are compared in Fig. 3 which shows the relative effective strengths of the received signals for a given peak transmitter power. In the case of single-current systems it should be noted that the receive relay or other receive element should be biased at a level corresponding to approximately half the effective signal amplitude. Thus only about one-half of the effective signal is operative in holding the receive element against the effects of noise. This has been shown in Fig. 3 by a horizontal line dividing the amplitude.

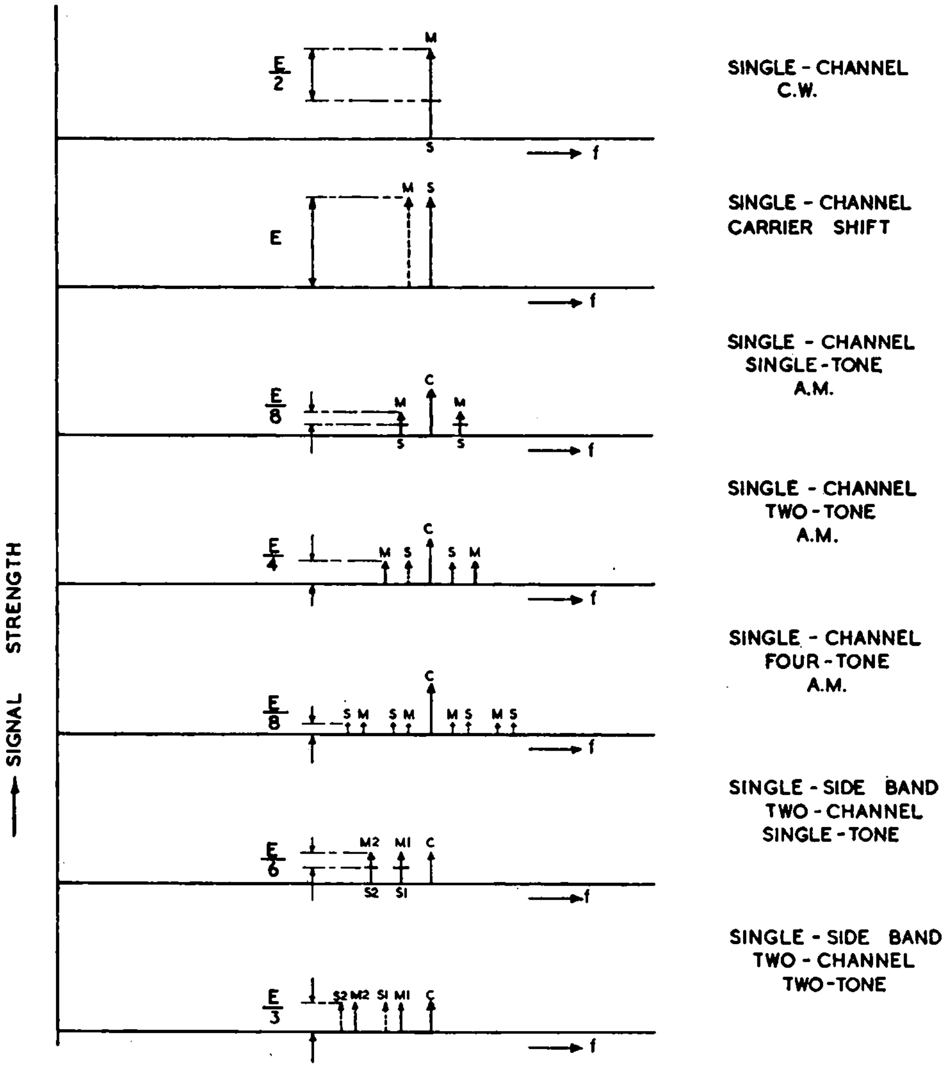
Modulation (1)	*Single-current* (2)	*Double-current* (3)
Direct	C.W. (on-off)	C.S.
Tone A.M. or F.M.	Single-tone	2-, 4-, or 6-tone
Tone, S.S.B. ..	Single-tone	2-tone

Table 1—Comparison of modulation systems

52. The actual choice from the many possible systems for a particular application depends upon the characteristics of the radio link (noise, fading, etc.), whether fixed or field, the amount of traffic to be handled and whether it is cyphered or uncyphered and so on. It is only possible to make recommendations in the most general terms as developments in a particular system may change the situation. Broadly speaking, single-current systems are to be avoided, although they may find wide application in future U.H.F. radio. The double-current systems are preferable for most other applications. For the long-distance fixed services, tone systems of multi-channel working seems to be preferable, but this aspect will be considered more fully below. Accepting these general principles as a guide, the choice of system is given in Table 2, although every case must be considered on its merits.

Type of Link	*H.F.*	*V.H.F.*	*U.H.F.*
Over 1,000 miles (fixed)	(*a*) Single side-band with tone multi-channel (*b*) Carrier shift		
100 to 1,000 miles (fixed and field)	(*a*) Carrier shift (*b*) 2-, 4- or 6-tone on A.M.		
Less than 100 miles (field)	(*a*) Carrier shift (*b*) 2-, 4- or 6-tone on A.M.	(*a*) 2-tone A.M. or F.M. (*b*) Tone multi-channel on A.M. or F.M.	(*a*) Single-tone (*b*) 2-tone (*c*) Tone multi-channel

Table 2—Effect of frequency on range of link



C= CARRIER AMPLITUDE
M= MARK SIGNAL AMPLITUDE
S= SPACE SIGNAL AMPLITUDE
† INDICATES SIGNAL HALVED DUE TO BIAS IN RELAY OR OUTPUT CIRCUIT FOR SINGLE - TONE ON/OFF WORKING

T A-172 / 1-3

Fig. 3—Relative amplitudes of systems of modulation

Sub-carrier modulation

53. A further system of modulation which will be described for the sake of completeness is that used in facsimile transmission. A sub-carrier of, say, 1,500c/s is transmitted over a tone type of radio link (A.M., F.M. or S.S.B.), and is set to provide 100% modulation. This tone is then frequency-modulated at a frequency of, say, 420c/s for transmitting a mark, and at, say, 540c/s for transmitting a space.

54. At the receiving end the F.M. tone may be limited and passed to a discriminator, followed by the usual 420c/s and 540c/s mark and space filters. This system appears to be promising in that it offers slight improvements where noise and selective fading occur together. It is also flexible in that facsimile equipment could be applied to such links.

MULTI-CHANNEL SYSTEMS

55. The maximum operating speed of a teleprinter is 66 words per minute. In practice operators cannot exceed 30 to 40 words per minute over long periods. This represents a severe reduction when compared with the 100 to 200 words per minute that has been used successfully with automatic morse tape systems. To increase the traffic-handling capacity of teleprinter links, it is necessary to use multi-channel working so that two or more separate teleprinter channels can be derived from one radio link. It is obvious that a radio link for multi-channel teleprinter working must be of higher signal-to-noise ratio than for a single teleprinter channel. Similarly a channel for high-speed morse must be superior to one for low-speed morse. For this reason it has been common practice to reduce the speed during deteriorating radio conditions.

56. It is very desirable that a multi-channel radio teleprinter link should be flexible in order that the number of channels can be varied to suit the radio conditions. With deteriorating conditions the number of channels can be reduced, thus maintaining a good standard of accuracy per channel.

57. As with telephony, there are two methods of achieving multi-channel telegraph operation, viz.:—

(*a*) Time division

(*b*) Frequency division

Each system has its merits and these will now be considered in detail.

Time division multi-channel systems

58. For an N-channel system operating on the time division principle the common transmission system is used for $\frac{1}{N}^{th}$ of a signal element by each channel. The early Baudot system is an example of this type. Fig. 4 shows the principle of this system. Some means of synchronization is necessary to keep the channel selecting wiper arms in synchronism. Actually a mechanical wiper is not essential and electronic distributors have been devised. Some form of signal storage element is also necessary so that the teleprinter keyboard can be operated independently of the wiper arm.

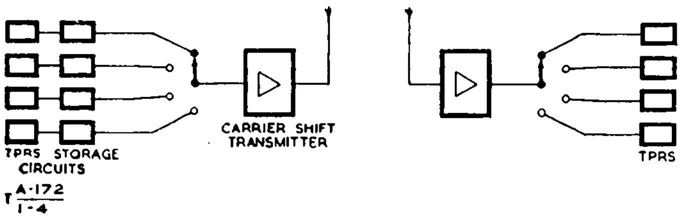


Fig. 4—Simple time division multi-channel system

59. The transmission link has to be capable of handling N times the telegraph speed of one channel. Thus filter widths have to be greater and for the same signal-to-noise ratio the signals have to be correspondingly stronger.

60. Difficulties with this system are liable to arise on long radio links subject to multi-path effects. Consider for example a 4-channel teleprinter multiplex system. The element length will be $\frac{20}{4} = 5$mS. ; that is, the radio link must transmit elements of 5mS. with a distortion maximum of about 2mS. When multi-path effects producing random delay differences of 2 or 3mS. have to be contended with, it is easy to see that a time division system may be unsatisfactory on such links.

61. The advantages of time division are that the equipment can be relatively simple and it need not be bulky. Flexibility of the number of channels can usually be provided with this system. To obtain the maximum gain over noise, the filter width should be reduced as the speed is reduced; this involves supplying a range of filters.

Frequency division multi-channel systems

62. In the frequency division system a separate tone frequency is allotted for each channel, or if the system is 2-tone, then there are two tones per channel. Such a system can operate only over a link capable of transmitting a band of audio frequencies. Such links are normal A.M. or F.M. links or single sideband (S.S.B.) links. Whether the system is single- or 2-tone, the radio equipment has to be capable of transmitting N tones simultaneously. The tones selected are usually those employed in line telegraphy, namely, 420c/s, 540c/s, 660c/s and so on, with 120c/s spacing. These frequencies are odd harmonics of 60c/s and are so chosen that the even harmonics of the lower channel tones, which may be produced during passage through the transmission link, fall in between higher channels and thus do not cause inter-channel interference. Odd harmonics of tones, especially the third harmonics, do coincide with higher channels and can cause inter-channel interference.

63. It is evident that with a frequency division multi-channel system the percentage modulation of the radio carrier per channel must be much lower than for a single-channel link. If the telegraph tones are generated by free-running oscillators, then it is possible for the instantaneous voltages of all channels to reach their positive peaks at the same instant although the probability of this is not high. If the radio equipment is not to be overloaded, then it is clear that the modulation per channel must be $\frac{1}{N}^{th}$ of the maximum permissible modulation. A typical instance of this kind is illustrated in Fig. 6(a) where a frequency group of three tones and the resultant wave envelope are shown. If now the phase of the upper or lower tone is moved through 180° at the reference instant, the envelope has a peak amplitude of 2.25 units instead of 3 units as in the previous case. Suitable phasing of a second similar group of three tones permits six tones to be transmitted

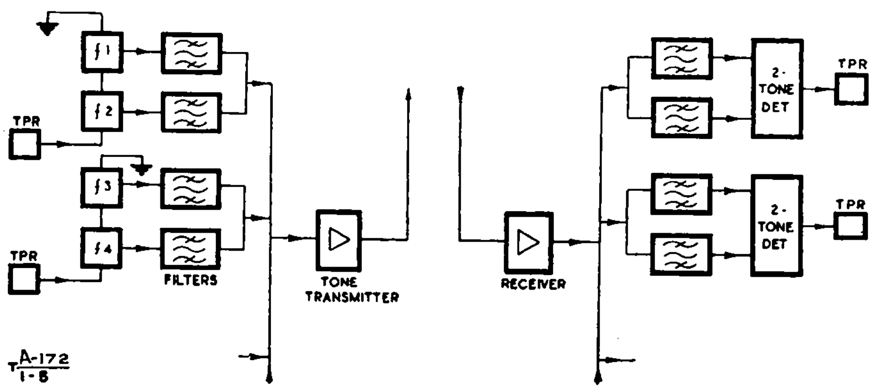


Fig. 5—Simple frequency division multi-channel system

with a peak envelope amplitude of 3.25 units. Fig. 6(b) illustrates this point. Thus careful phasing of the telegraph tones will permit a higher modulation per channel than $\frac{1}{N}$ to be achieved with a consequent stronger signal in each channel. This phasing can be achieved by using rotary tone generators or oscillators suitably locked to a 60c/s fundamental oscillator. The mathematical treatment of Fig. 6 is dealt with in para. 135–138.

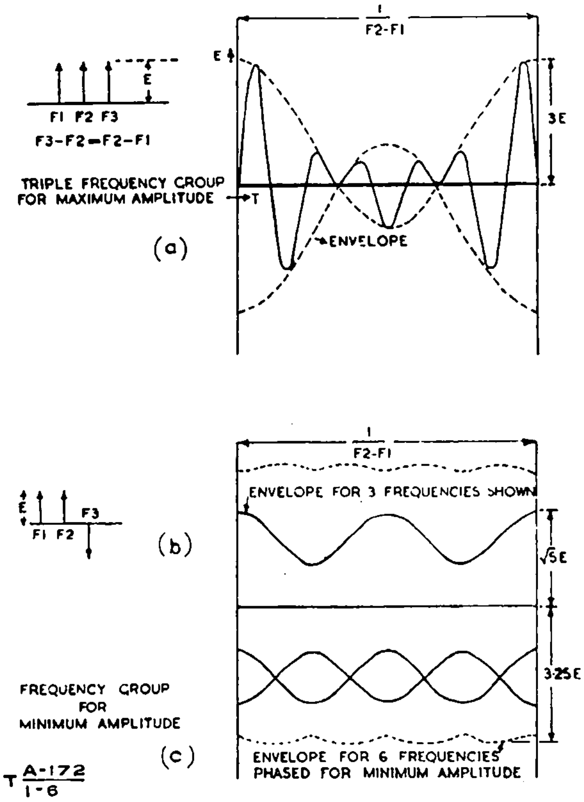


Fig. 6—Envelopes of multi-tone systems

64. If this phasing of the tones is not used, then the signal-to-noise ratio of the radio link for 100% modulation must be 20 log N decibels better than for a similar type of single-channel link. Actually a concession of 3 to 6db. can be allowed on this figure for 6 to 12 channels respectively, to allow for the fact that the probability of all channels peaking simultaneously is not large.

65. From the point of view of distortion due to noise there is little to choose between time division and frequency division multi-channel working, provided the radio system is of the single sideband type in the latter case. Where multi-path effects and fading have to be contended with, as on long-distance radio, there seems no doubt that frequency division is most satisfactory, since with this system the teleprinter elements are still 20mS. long and 2 or 3mS. distortion can be well tolerated.

Existing multi-channel V.F. telegraph equipments

66. The main British Army V.F. telegraph equipments, designed primarily for use on line are :—

(*a*) Apparatus, V.F. telegraph, 3-channel, duplex.

(*b*) Apparatus, V.F. telegraph, speech plus duplex.

The units of the first equipment can be assembled so as to provide up to six channels for telegraph working over a 2-wire audio circuit, or up to twelve channels over a 4-wire audio circuit. The second equipment provides one speech channel and one duplex (2-way) telegraph channel over a 2-wire audio circuit.

67. The telegraph channels are obtained by the use of audio frequency tones from 420c/s to 1,980c/s which may be interrupted by teleprinter or hand speed telegraph signals. Each tone representing a channel is generated by a valve oscillator and passed through a filter. The outputs of the filters of the several channels are connected in parallel and pass to the line for transmission. At the receiving end of the line the tones are separated into the various channels by a similar set of filters. After rectification the tone signals are caused to operate a relay which passes the signal on to the receiving teleprinter or other receiving instrument.

68. The receiving telegraph detector has automatic gain control which caters for lines of 0—55db. attenuation. It also incorporates an automatic bias feature which enables the relay to operate at one-half of the received level of the single-tone signal. The time-constants of these circuits are designed for line use only and are of the order of 15 seconds. With single-tone working the time-constant must in any case be large compared with the length of a character (140mS.). This conflicts with the requirements for a telegraph detector for use on radio links, where a time-constant comparable with the telegraph element length is desirable to cope with rapid fading.

69. Thus this type of line telegraph equipment is suitable only for use on radio links of the V.H.F. or U.H.F. type where the performance is comparable with that of a line.

TRANSMITTER SYSTEMS

70. The method of transmitting the outgoing radio teleprinter signals depends upon the type of modulation adopted. C.W. systems are discussed in paras. 34-36. Carrier shift transmitter systems will be briefly touched upon. The tone systems will also be briefly described.

Carrier shift systems

71. The simplest system is that in which the master oscillator of the radio transmitter is of the coil and condenser type. The carrier shift signal may then be obtained by keying a suitable value of capacitance across the master oscillator tuned circuit. This capacitance will have to be adjusted to produce the correct frequency shift at various transmitted frequencies. If the master oscillator is followed by frequency multiplication stages, the shift produced by the condenser must be the appropriate sub-multiple of the shift.

72. The keying of the trimmer condenser may be effected by a telegraph relay or by means of an electronic switch, for example, a diode whose bias can be controlled by the telegraph signals. This method of deriving carrier shift is shown in block diagram form in Fig. 7(a). It is a satisfactory method, its main limitation being the frequency stability which must be achieved with receiving systems incorporating narrow filters. To improve frequency stability, keying of a condenser across a crystal master oscillator has been attempted. This method is not to be recommended, however, because it is difficult to achieve stability of the amount of the frequency shift ; special

crystal cuts are also necessary. To overcome this difficulty a circuit has been designed in which the output of a crystal master oscillator is modulated by an audio frequency of one-half of the shift required. For example, for 850c/s shift, with no multiplication, the M.O. output is modulated in a balanced type of modulator with 425c/s. This produces two sidebands of fc±425c/s with the carrier frequency (fc) suppressed to a low level, depending on the balance achieved in the modulator. In a similar modulator the same radio frequency (in the same phase as the first modulator) is modulated with 425c/s which is 90° out of phase with the 425c/s in the first modulator. Combination of the outputs of these two modulators causes, say, the upper sidebands to add and the lower sidebands to cancel one another. Reference to Fig. 7(b) shows the general principle. If now the phase of the 425c/s fed to the first modulator can be shifted through 180° when it is desired to transmit a space, then the lower sidebands add and the upper sidebands cancel. This 180° shift is produced by passing the positive and negative signals through a ring modulator of metal rectifiers. This functions as a simple reversing switch and provides the 180° phase shift of the 425c/s. This type of frequency shift equipment is difficult to design, especially to cover a wide range of radio frequencies in the H.F. band. It is also difficult to achieve adequate suppression of the unwanted carrier and sideband.

73. A more practical type of frequency shift master oscillator is shown diagrammatically in Fig. 7(c). This uses the principle of interpolation oscillators. The transmitted radio frequency is derived by adding a frequency of, say, 200kc/s to a frequency derived from a crystal oscillator. The 200kc/s oscillator can be of a high-stability coil and condenser type, the frequency of which can be shifted the desired 850c/s by using a capacitor keyed by the telegraph signals. Thus something like 95% of the outgoing frequency is of crystal oscillator stability, the remaining 5% being of good coil and condenser standard. The 200kc/s is added by producing upper and lower sidebands on the crystal oscillator output with a balanced modulator. Suppression of the unwanted lower sideband and any residual crystal oscillator leak is carried out by simple tuned circuits. The crystals required for this arrangement have to be cut for a frequency of, say, 200kc/s away from the transmitted frequency. This introduces a slight objection to the scheme. If the interpolation oscillator were made 465kc/s and the lower sideband selected, then the crystal would be standard with the crystal in the receiver.

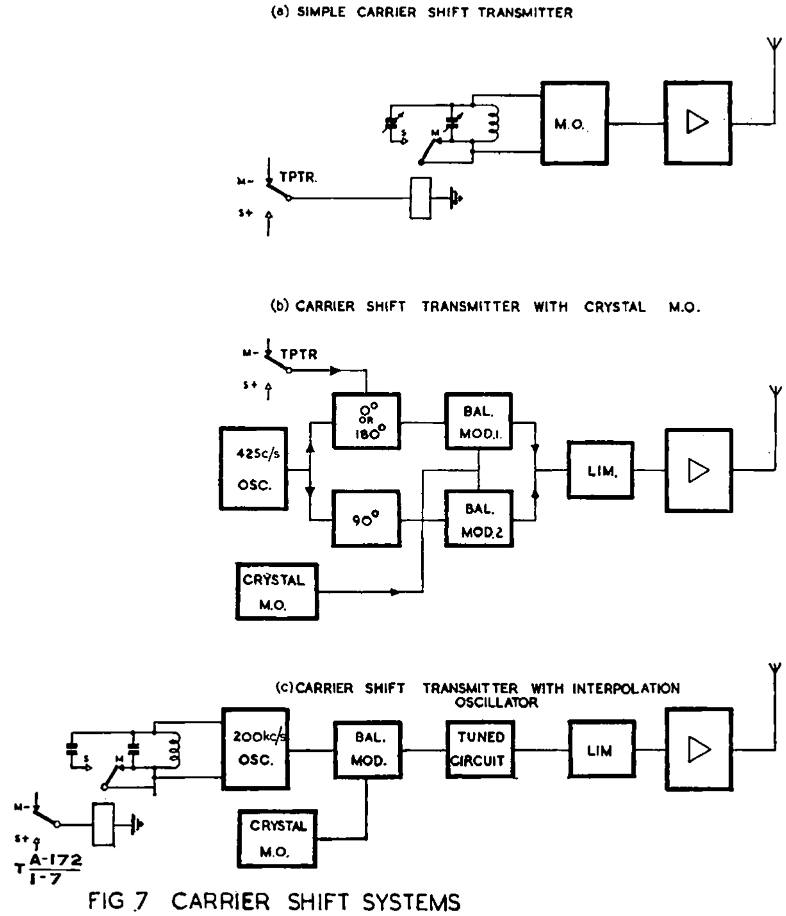


Fig. 7—Carrier shift systems

74. The shift of 850c/s, which has been mentioned in describing these systems, is fast becoming standard in the U.S. and U.K. In Germany a shift of 360c/s was used. The smaller shift permitted the use of a narrower I.F. filter, but the improvement in performance under noise conditions was very slight. The smaller shift aggravates the frequency drift problem, so that there seems little

object in departing from 850c/s. There is some case for a frequency of 840c/s since this is a multiple of 120c/s, the standard V.F. telegraph spacing, but the difference from 850c/s is insignificant.

Tone systems

75. The transmitter should be capable of transmitting a band of 300c/s to approximately 2,500c/s with small frequency and harmonic distortion. The additional equipment necessary at the transmitting end is a source of tones and a means of modulating or keying them with the teleprinter signals.

76. For 2-tone systems, a tone oscillator with a tuned circuit may be employed. A capacitor may be keyed by a relay across the tuned circuit to change from one tone to the other. In compact installations care must be taken to ensure that the means of keying does not cause radio interference. If a relay is employed, it must be radio-suppressed, and as capacitors must be employed for suppression, their effect on the tuned circuit must be taken into account. An alternative scheme which has been employed in the British Army is the use of separate tone oscillators, one for each frequency, with keying between oscillators carried out by means of metal rectifier modulators.

77. For multi-channel or frequency diversity systems a multiplicity of such oscillators may be used. If phasing between tones is aimed at in order to secure maximum efficiency, then rotary tone generators or phased oscillators locked to a master must be employed.

78. Where two tones are used it is desirable to pass them through transmitting filters before modulating the radio equipment. For multi-channel or systems of more than two tones, the use of transmitting filters is essential. If such filters were not used, the transmitted signals would be tones of, for example, 900c/s with a square-wave modulation of, say, 50 bauds. Such signals have sidebands of ±25, ±75, ±125c/s, etc., of gradually diminishing amplitude. These sidebands would cause serious cross-channel interference. Even in the single-channel 2-tone case they can cause telegraph distortion, so that transmitting filters are again desirable.

RECEIVING SYSTEMS

79. The radio frequency circuits of the receiving system follow conventional practice. They are invariably of the superheterodyne type. The signal from the intermediate frequency filter may, however, be detected in several ways which depend broadly upon whether they are carrier shift signals or multi-channel tone signals. Before passing to a detailed consideration of these detection systems, reference will be made to a few points which must be observed when selecting or designing a receiver for radio teleprinting.

80. The first point concerns selectivity. In para. 110 the desirability of passing the signals through narrow filters is stressed. Ideally these filters should be at the radio frequency, but this is not possible because of the narrowness and sharpness required. The filtering has therefore to be carried out at intermediate or audio frequency. Nevertheless the radio circuits should be as selective as possible before frequency changing is carried out and before too much radio frequency gain is introduced. This is necessary to prevent blocking of the receiver by interfering signals. Furthermore, to prevent interfering signals from mixing with one another during frequency changing and then penetrating subsequent filters, the centre frequency of each filter should preferably be greater than the band-width of previous filters.

81. The I.F. filter should have a uniform loss in the pass band and the signals should pass symmetrically with respect to the centre frequency of the filter. This is desirable in order to preserve the symmetry of signals, especially those of the 2-tone or carrier shift type.

82. A further point concerns the stability of the receiver oscillators. This stability cannot be too high, especially with carrier shift systems. In the case of single-sideband systems some form of automatic frequency control is essential.

Detection systems

83. Detector systems may be divided into two chief types:—

(*a*) Those which rectify directly the radio frequency signal, or some frequency-changed derivative (i.e., the I.F. of it).

(*b*) Systems in which the modulation on the carrier is in the form of tones, these tones being demodulated and then passed to a tone detector.

84. In the first type the signal is usually taken from the final I.F. stage of the receiver and fed to a frequency discriminator (see Fig. 10 and para. 89), while in the second type the signals from the I.F. amplifier are heterodyned with a further oscillator to produce audio tones. These tones are then demodulated and passed to a tone detector.

Single-tone dectectors

85. A single-tone detector will in general include a filter for selecting the desired tone, an amplifer and a tone rectifier, followed by an output stage driving the receive relay. A means must be provided to operate the relay to space on the cessation of the tone. This may be an electrical bias on the relay equivalent to half the amplitude of the received signal. This bias must be adjusted during the setting-up of a circuit. Automatic bias circuits have been evolved which provide this half-amplitude bias automatically. These bias circuits must have a long time-constant compared with the element length, to preserve the bias during a succession of spaces. In the case of radio circuits subject to fast fading, it is clear that such detectors are not likely to be highly satisfactory. This is one of the inherent difficulties of single-tone detection.

86. On radio circuits using V.H.F. or U.H.F. frequencies, where the performance approaches line, these difficulties do not arise. The type of single-tone detector used in line practice can be applied with success to such circuits. The principle of one such detector is shown in Fig. 8. After tone filtration and amplification, the signal is passed to four rectifier circuits, M1, M2, S1 and S2. Of these circuits M2 and S2 have long time-constants and they provide D.C. bias voltages equal to half the signal envelope amplitudes. M2 also provides A.G.C. voltages to the pre-amplifier. When tone is present, M1 provides a positive voltage which is double the negative voltage of M2, and S1 provides a negative voltage double the positive voltage of S2. Thus V_m has a net positive signal on its grid and V_s a net negative signal on its grid. On cessation of the

tone, the bias voltages only are present and V_m has a net negative signal while V_s has a net positive signal. With the potentiometer set for no bias the output circuit thus passes symmetrical double-current signals on to the relay. This condition is preserved automatically by the bias circuits over a range of levels of input tone as wide as 55db. Other features are included in the detector, but they are not important for the present purpose.

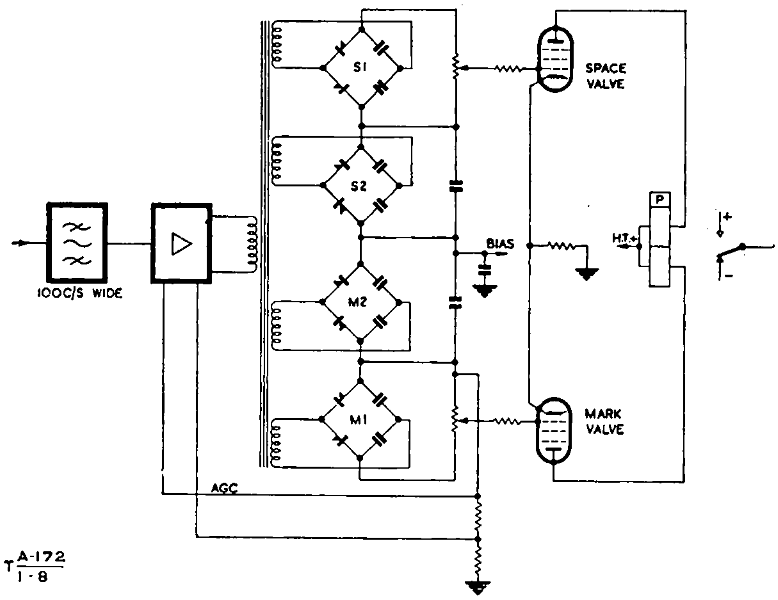


Fig. 8—Single-tone detector

2-tone detectors

87. Several types of 2-tone detector have been employed. The most usual type is that in which the two tones are passed through two filters, one for each tone. Having thus separated the mark and space tones, they are amplified, rectified, smoothed and applied to the output stage which has two valves in push-pull with a polarized relay as shown in Fig. 9. The circuit shown is that used in some Army equipments. It will be noted that the two output valves have a common cathode resistor and a common screen grid resistor. Referring to Fig. 9, during the change from mark to space, as soon as the space signal grid voltage commences to exceed the mark signal grid voltage, the current in the mark valve is rapidly reduced due to the rise of cathode voltage and the fall of screen voltage. The latter is due to the increasing current taken by the space valve; thus the current in the relay is rapidly reversed when the two grid voltages are equal.

88. The rectifier smoothing time-constant is 5mS. and is designed to smooth the full-wave-rectified tone. The circuit RC has a time-constant of 10mS. This circuit provides a negative bias whenever the signals are strong enough to cause the output valves to take grid current. Should the signals fade, causing the grid current to cease, C discharges in a time less than a signal element (20mS.). Thus quite rapid fades can be dealt with.

89. A further type is that in which the two tones are passed to a frequency discriminator as shown in Fig. 10; a typical characteristic is shown in Fig. 11. If the mid-frequency of the mark and space tones coincides with the mid-frequency of the discriminator, the teleprinter D.C. signals will be produced without bias. If there is a drift of the two tones, bias will be produced. Further reference to this aspect will be made in paras. 94-97.

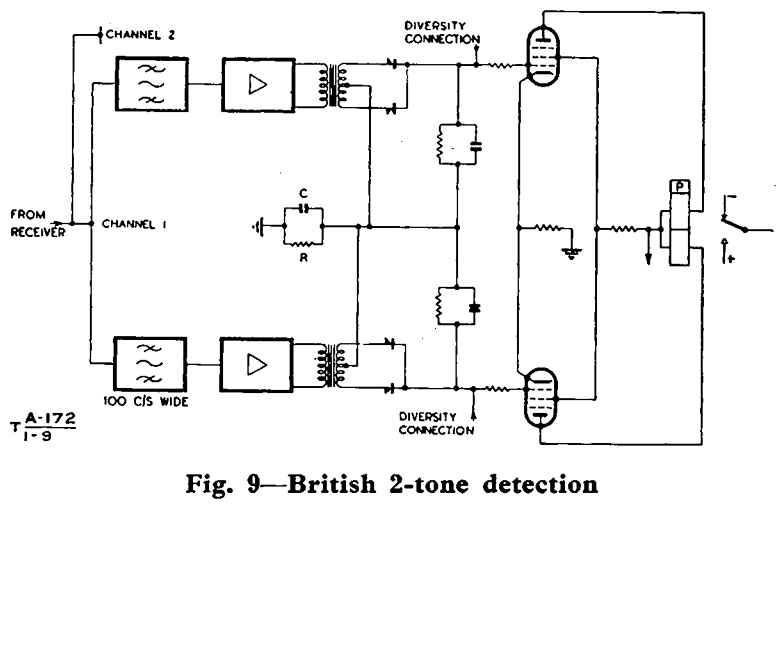


Fig. 9—British 2-tone detection

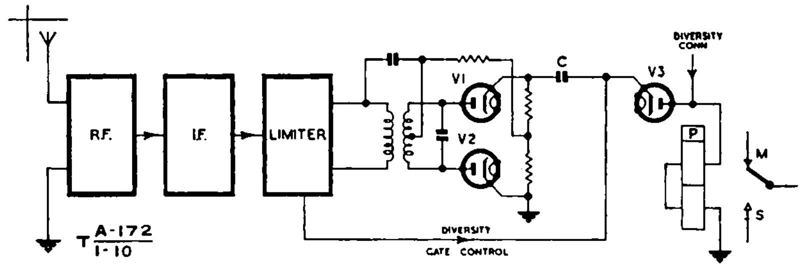


Fig. 10—F.M. discriminator detector

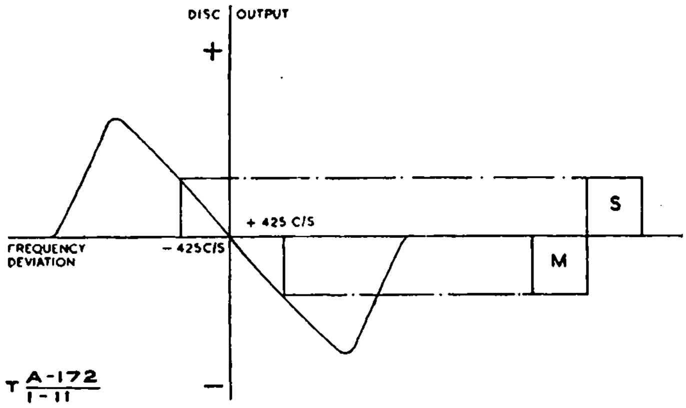


Fig. 11—Discriminator characteristic

90. A type of 2-tone detector widely employed by the German Army is illustrated in Fig. 12. The two tones are passed through a filter embracing the two tones. The circuit then branches to two simple phase-shifting circuits. One circuit shifts tones M and S through a phase of 90°. The other circuit shifts M tone 90° and S tone 270°. After amplification the M tones (or the S tones) are passed to a ring modulator which functions as a phase detector. The M tones are in phase so that the polar relay operates to the M contact. The S tones are in anti-phase and the output of the phase detector causes the relay to operate over to the S contact.

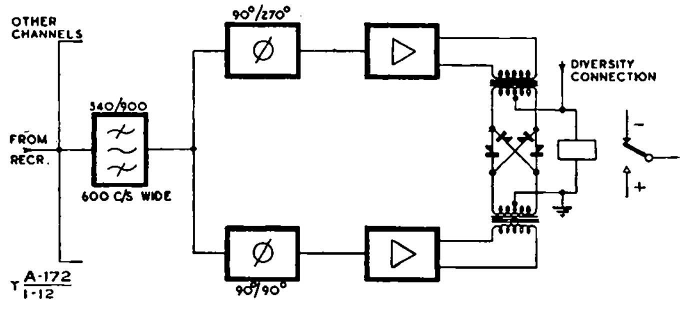


Fig. 12—German 2-tone detector

4- and 6-tone detectors

91. As stated in para. 41, to combat selective fading on long sky wave circuits, two tones can be used for mark, followed by two other tones for a space. In German practice, six tones were used, three for mark and three for space. This constitutes frequency diversity which may be used as an alternative to space diversity. In the British 4-tone case (Apparatus, telegraph, 2/4-tone, No. 5) there are four filters and two tones of 420c/s and 1,860c/s represent a mark, and 540c/s and 1,980c/s represent a space. The wide separation between mark tones and space tones were chosen to reduce the chances of both tones fading together. A 2-tone detector of the type shown in Fig. 9 is provided for the 420/540c/s pair and another for the 1,860/1,980c/s pair. The detectors are combined at the points shown in Fig. 9. It will be seen that the largest mark voltage and the largest space voltage are applied to the output stage. Thus, if one mark tone is subjected to a fade, the remaining mark tone preserves signalling. This may be called "peak combination." An alternative point of combination is at the anodes of the output stage. With this connection the average of the two tones is selected rather than the larger of the two. This may be called "average combination." In general the former connection is to be preferred because the weaker signal, which would tend to have the worst signal-to-noise ratio, is rejected. A further method of diversity combination or switching is to select the diversity channel having the best signal-to-noise ratio. This switching is best achieved by an electronic switching system which must be capable of operating at a speed which does not influence the receive relay or element.

92. Apparatus, telegraph, 2/4-tone, No. 5 was designed to provide maximum flexibility. Besides the 4-tone system described above it may be adjusted to work 2-tone with space diversity or 2-channel 2-tone. Limiters which may be switched in or out are provided and peak or average diversity combination may be used.

93. The German 6-tone detector employs three detectors of the 2-tone type depicted in Fig. 12. It will work 3-channel 2-tone or single-channel 6-tone with average diversity combination.

Carrier shift detecting systems

94. One method of detecting carrier shift signals is that of reducing the I.F. output by a B.F.O. down to 2-tone signals and then detecting by one of the methods given in paras. 87-90. It will be realized that any frequency drift at the transmitter, receiver first oscillator, or B.F.O. will cause a drift of tones. If narrow selecting filters, e.g., 100c/s wide, are used, the frequency stability requirements are very high. Automatic frequency-control circuits may be used. Such circuits need very careful design, owing to the narrow limits of drift and the fact that the control tone, e.g., the mark tone, is interrupted with telegraph signals. Frequency drift alarms have been operated off the mark tone as in the Equipment, signalling, carrier shift, No. 1. A discriminator operating a centre-stable relay is used which gives a high- or low-frequency alarm as soon as the drift exceeds a predetermined figure.

95. To overcome the frequency drift problem, considerable thought has been given to a system in which the I.F. output is limited and passed directly to a discriminator, thus producing the negative and positive teleprinter signals directly if the frequencies are correct. The block schematic is shown in Fig. 8. As stated previously, frequency drift now produces signal bias which must be reduced if distortion is to be kept down. A drift exceeding 425c/s (with U.S. and British equipment 850c/s shift) would cause relay change-overs to cease unless other steps were taken. To preserve signalling during frequency drifts, the teleprinter signals may be passed through capacitors. These capacitor circuits may have a long time-constant compared with signal elements, or a short-wave constant. In the first case, during periods of no traffic, the condensers will discharge, leaving the output relay or circuit with no holding current. In this condition the output circuit is prone to disturbance by noise. Efforts to apply D.C. restoration have been made to overcome this difficulty. An alternative method of overcoming the frequency drift problem consists of passing the teleprinter signals through a transformer with a secondary time-constant large compared with the element length. D.C. restoration can then be successfully applied by means of signals reintroduced in the secondary by a relay connected in the output circuit.

96. The case of the series capacitor with short time-constant compared with an element length corresponds to differentiation of the teleprinter signals. A short negative pulse will be produced by a positive-to-negative change-over, and a short positive pulse by a negative-to-positive change-over. These pulses are passed on to a side-stable circuit or relay. This scheme has one possible advantage in that it continues to signal if either mark or space frequencies are subject to a complete fade. It is, however, prone to disturbance by noise because during idle periods the signal is not effectively employed. This is especially true since the I.F. has to be made considerably wider than the frequency shift to allow for possible drifting. The lack of a narrow filter as in the tone schemes permits greater disturbance by noise.

97. These systems are still largely in the experimental stage. There is evidence that for fixed services the problems are solved as completely as possible by the use of temperature-controlled crystal transmitters and receivers, with conventional 2-tone detectors. The study of less elaborate schemes of carrier shift transmission is, however, well worth while.

Single-sideband systems

98. A single-sideband receiver is designed to receive a vestigial carrier and an upper or lower sideband of frequencies of about 300c/s to 4kc/s. The S.S.B. radio transmitter and receiver are thus capable of transmitting a normal speech band of frequencies. To provide teleprinter circuits, it is now necessary to apply equipment preferably of the 2-tone or 4-tone type.

99. Single-sideband equipment is very suitable for the application of multi-channel tone equipment. Up to six 2-tone teleprinter circuits have been derived from long-distance radio circuits of this type. The maximum economy in transmitter power is achieved for the best possible signal-to-noise ratio at the receiving point.

100. Selective fading can be troublesome and space or frequency diversity can be applied to overcome these difficulties. The usual methods of combination of the diversity channels are used. The single-sideband system does, however, show marked advantages over A.M. double-sideband systems with sky-wave transmission and selective fading. The demodulated output tones are independent of the relative phase of the vestigial carrier and the sideband in the S.S.B. system. Furthermore the vestigial carrier is reconditioned by limiting before being used for demodulation, thus removing one variable factor in the process. With ordinary amplitude modulation, a phase shift of the carrier with regard to the sidebands can reduce the tone output to a low level although the carrier and sideband amplitude are normal. Further with A.M., independent fading of the carrier causes variations of output tone level.

101. Up to the present it is believed that diversity has not been successfully applied to the vestigial carrier ; with this addition such systems should prove very reliable.

102. The similarity between 2-tone working on S.S.B. links and carrier shift working has already been noted (para. 46). It should be observed that the steady vestigial carrier in the S.S.B. case provides more reliable frequency control than can be obtained from the interrupted mark carrier of carrier shift signalling.

Limiters

103. Carrier shift signals and 2-tone signals may be passed through amplitude limiters before separation of the mark and space elements. 4- and 6-tone signals can be passed through limiters after separation into mark and space pairs, but before separation into mark and space elements. These limiters are usually of the conventional valve types used in F.M. receivers and should have a very short time-constant compared with the signal frequency.

104. The use of a limiter ensures that the detector is supplied with a signal of constant amplitude as long as the incoming signals are above the threshold of the limiter. The limiter also tends to improve the ratio of mark signal to space noise and vice versa. The improvement is about 5 or 6db., except when the voltages in the two paths are nearly equal.

105. Limiters do, however, increase the distortion of the telegraph signals, especially when they have already passed through narrow filters. The decay of the mark tone is combined with the build-up of the space tone in random phase at the limiter input. Limiting and subsequent separation of the tones causes the instant of change-over in the detector to be somewhat random during the decay and build-up period.

106. The benefit or otherwise of limiters can be proved only by very extended field trials. In some cases they may be beneficial and in other cases they may be unsatisfactory. Much depends upon the character of the interference. Further work on this problem is indicated.

107. In the case where the signals have not passed through narrow filters, either at the sending or receiving ends, the time of decay and build-up is small, and it seems that limiters will give an advantage. This applies especially to the system of detecting carrier shift signals by passing the I.F. output through a limiter to a frequency discriminator.

Diversity reception

108. On long-distance radio links using sky-wave transmission, selective fading can occur. Two radio frequencies

of equal transmitted amplitude and only 100c/s apart can be received with momentary amplitude differences of at least 15db. Due to interference between waves arriving at the receiving aerial after having travelled over different paths, one of the frequencies may be received strongly while the other is subject to a deep fade. A second or so later the strong signal may fade while the weak signal rises to a strong one. The phenomenon occurs together with multi-path effects (para. 22). With 2-tone transmission on a link subject to this phenomenon, misprinting is very liable to occur.

109. There are several precautions to be observed to minimize this trouble. The time-constant of the 2-tone detector A.G.C. must be short compared with a telegraph element (para. 87); limiters in the 2-tone path may be employed (para. 103). The most satisfactory method is no doubt the use of space diversity, that is, the use of two or three receiving aerials, with independent receivers and tone detectors. The signals may be combined by the peak method or the average method as in para. 91. Where the receiving layout must be compact the use of 4- or 6-tone working with a single aerial gives frequency diversity which can give satisfactory results (para. 91).

Band-width of receiving filters

110. It is desirable to pass the signals through a narrow filter to minimize interference by noise and other unwanted signals. The lower limit to the band-width is set by the character of the noise, i.e., whether steady or impulsive, and by the distortion of the wanted signals. As explained in paras. 79-82, this filtering should preferably be carried out at an early stage in the chain of receiving circuits, or the early circuits should be as selective as practicable, with the narrow filter in the I.F. or audio stage. With the latter precaution it may be assumed that the narrowest filter in the chain is the effective one.

111. Consider an idealized band-pass filter of band-width f_b c/s., then the time of growth of a suddenly applied signal at the mid-band frequency is approximately :—

$$t = \frac{1}{f_b} \text{ seconds}$$

The time of decay on sudden removal of the signal is identical. If the noise is of the random type, the noise power penetrating the filter is proportional to the band-width. That is :—

$$n^2 \doteq k^2 f_b$$

where n is the R.M.S. noise voltage over a long period, and k^2 is a constant depending upon the intensity of the noise.

112. In the case of the C.W. system, the noise passes freely during the space (Fig. 2(a)). When the signal starts to build up, the noise and signal voltages add to one another. The phase of the noise and signal bear a random relation to one another, and this must be taken into account in carrying out the addition. Sometimes the noise appears as a positive increment on the signal envelope and sometimes it is negative and reduces the envelope.

113. It has been shown that the probability of a time displacement between x and (x+dx) when the envelope crosses the relay operating level (Fig. 2(a)) follows approximately the normal law, and its standard deviation $\bar{x}$ can be calculated from :—

$$\frac{\bar{x}}{n} = \frac{\frac{1}{f_b}}{E\sqrt{2}}$$

where *E* is the R.M.S. of the signal voltage. A linear peak detector is assumed. Hence we have

$$\bar{x} = \frac{n}{Ef_b\sqrt{2}} = \frac{k}{E\sqrt{2f_b}} \quad \text{(since } n = k\sqrt{f_b} \text{ from para. 111)}$$

From this formula if f_b is made too narrow, excessiv misprinting will be caused by large values of x.

In the space period the noise envelope is always positive and it follows the Rayleigh probability law (i.e., the probability of a noise voltage between y and (y+dy) is

$$dp(y) = e^{-\left(\frac{y^2}{2n^2}\right)} \cdot \frac{y}{n^2} \cdot dy$$

with a standard deviation of $n\sqrt{2}$. Hence

$$\bar{n} = n\sqrt{2} = k\sqrt{2f_b}$$

The probability of the noise voltage exceeding the bias voltage (E/2) can be calculated. If f_b is made too wide, there will be excessive misprinting due to noise operating the relay as at *A* in Fig. 2a.

115. The best filter band-width is that in which the probability of misprinting due to the two causes is of the same order.

116. From the Rayleigh law we may deduce that the probability of the noise voltage during space, exceeding $\frac{E}{\sqrt{2}}$ is given by

$$e^{-E^2/4n^2}$$

Suppose we assume a misprinting probability of 0.001 for both causes, or 0.0005 for each cause. Then the signal-to-noise ratio should be 5.5, corresponding to 15db. From normal law tables the probability of the time displacement exceeding various values may be deduced. For a probability of 0.0005 the time displacement is 3.5 times the standard deviation. Using this figure and the above signal-to-noise ratio in question (1), we get a time displacement of approximately $\frac{1}{2f_b}$.

The tolerance of the teleprinter receiving mechanism (7mS.) should be of this order for the above probability. Actually an allowance should be made for the fact that other parts of the transmitting and receiving circuits produce up to 10% characteristic distortion (i.e., 2mS.). Hence, if we set 5mS. equal to $\frac{1}{2f_b}$, we get a band-width of 100c/s.

117. The above considerations apply to random noise. Suppose now that there is interference of an impulsive type. A suddenly applied sinusoidal voltage whose frequency lies outside the transmission band of the filter, will produce a transient response at the output of the filter which has an envelope of approximately triangular form. The duration of this transient will be of value :—

$$t = \frac{2}{f_b} \text{ seconds}$$

118. Its peak amplitude will be proportional to f_b and, of course, proportional to the interfering voltage. Another compromise must be made here: if the filter is too narrow, the transients will be long compared with the element length although of small amplitude; if too wide, they will be short but of large enough amplitude to cause spurious

characters. These factors are difficult to assess since they depend upon the character of the interference. They lead in general to a similar figure to that above. The width of filters used in most V.F. systems for teleprinter signals is approximately 100c/s.

119. Practical considerations of frequency drift often dictate the use of wider filters. In Equipment, signalling, carrier shift, No. 1 the width is 500c/s to allow for drifting.

120. Similar arguments regarding band-width apply to a 2-tone system (Fig. 2b). Consider noise acting in one channel only; then the time displacements which it causes are approximately halved, and double the noise amplitude is required to cause a spurious operation as compared with the C.W. case. Actually there will be noise in both channels, and if these noise voltages are independent, the net time distortions and spurious operations will still be less than in the C.W. case. For the same probability of misprinting the double-current system can tolerate about double the noise voltage that the single-current system can tolerate. That is, it gives about 6db. improvement. The double-current system has other advantages, such as unbiased relays, simpler A.G.C. circuits and the possibility of limiting, which cannot be assessed in terms of signal strength.

Reception element

121. When the received radio signals are reduced to D.C. signals, they may be passed on to the teleprinter in two ways. They may be used to operate a sensitive polar telegraph relay which repeats local power on to the teleprinter, or they may operate mark and space valves which feed current to the teleprinter receiving magnet directly.

122. Up to the present time, the relay method has been used almost exclusively. It is, in general, very satisfactory, but precautions must be taken to ensure that radio interference generated by the relay contacts does not reach the radio receiver input. This may be ensured by a screened aerial lead-in, or by physical separation of the relay and radio equipment. These methods are often inconvenient, especially for field equipments, and it is necessary to suppress all telegraph relays with condensers and chokes. Suppression of relays for a wide band of radio frequencies is extremely difficult if not impossible. The valve output method is free from radio interference and has much to recommend it. There seems no doubt that this method should be further developed, especially for Army field use.

INTER-WORKING OF LINE AND RADIO LINKS

123. Inter-working of teleprinters on lines has been extensively employed in civil practice, and in the British Army a range of teleprinter switchboards has been used with success. These switchboards are of the manually operated type.

124. Where teleprinter channels are derived from high-stability V.H.F. or U.H.F. radio circuits they can be terminated on switchboards and inter-worked with line circuits without difficulty. There is no reason why circuits derived from H.F. radio links should not be terminated on switchboards and world-wide inter-working obtained. The German Air Force was reputed to have operated a system of the latter type in which long radio teleprinter circuits where switched to line circuits. The U.S. Signal Corps favoured a world-wide tape relay system in which links were operated on a point-to-point basis with receiving typing reperforators. In the latter system the teleprinter signals received over each link are stored by punching holes in paper tape; the letters corresponding to the holes are also typed on the tape. Operators at the relay stations feed the tape on to the appropriate 5-unit transmitters of the outgoing link, the routing information pre-fixing the signal on the tape. In future civil practice automatic switching and routing of line teleprinter circuits is to be used. Connections will be set up by the use of a dial as in an automatic telephone system. The answer back device of the teleprinter will ensure that the correct teleprinter has been selected before the message is transmitted.

125. In the British Army point-to-point working has been the rule, and it is probable that this practice will, to a large extent, continue for cyphering and traffic reasons. However, it is wise to consider inter-working as the flexibility of such systems may prove of value in an emergency. Tape relays are used for Army chain networks and in the field rear of Army H.Q.

126. When two telegraph channels are connected in tandem, the over-all telegraph distortion of the circuit can be the sum of the separate distortions of the two links. If a link has a distortion of 15%, it can be seen that inter-working of more than two links in tandem is not likely to be satisfactory. With the U.S. Signal Corps tape relay system the distortion of each link is corrected before passing the signals on to the next link. The receiving reperforators automatically provide this correction. When circuits are to be directly connected together, a teleprinter regenerator can be used at the receiving end of each link. Such a regenerator was used in the German system mentioned above. A short description of the principles of regeneration is given in the next section.

Regeneration of teleprinter impulses

127. Several types of regenerator are possible, but the fundamental principles are similar. The distorted signals are received character by character. The start signal of each character causes the ensuing five unit code pulses to be distributed to a storage system. The latter may be a mechanical system or an electrical system; for example, the character can be stored in five condensers. This reception system will store correct signals within the limits of a teleprinter system, i.e., provided the distortion does not exceed 35%, the correct character is stored. It is possible to design systems capable of storing correctly with distortions of rather more than this, up to a limit of about 45%. Having stored the character correctly, it is now only necessary to retransmit it with a distributor of low distortion.

128. The regenerator will introduce a slight delay of perhaps one character duration, but this is of no importance. Actually regenerators which do not involve character storage are in use. Thus the regenerator in the receiving path of a radio link can enable the link to work with a low over-all distortion. Many such links can now be operated in tandem with correct over-all printing.

129. The development and simplification of such regenerators is desirable, even if wide use of switched teleprinter

networks is not contemplated. A regenerator which has no complicated adjustments and can be relied upon to correct a distorted signal is a valuable instrument to use in conjunction with teleprinters. If switched telegraph links are contemplated, it is desirable that the regenerator should be capable of transmitting a long space (600mS.) for switchboard clearing purposes.

Telegraph distortion measurements

130. With the greater use of teleprinters for line and radio systems, there is a growing need for adequate telegraph distortion measuring equipment. There is a possible need for equipment providing the following facilities :—

- (*a*) Measurement of teleprinter transmitter distortion.
- (*b*) Measurement of teleprinter receiving margin.
- (*c*) Measurement of the over-all telegraph distortion of a transmission link.
- (*d*) Continuous monitoring and measurement of the distortion of received traffic teleprinter signals.

The last equipment is of special interest in connection with radio teleprinter systems. When a radio teleprinter system is carrying traffic and the radio channel is deteriorating due to atmospheric conditions or transmission path changes, the only warning of the oncoming conditions is incorrect printing. If, however, a distortion monitor is connected across the receiving end of the circuit, adequate warning of deterioration is given and consideration can be given to changes of radio frequency, aerial, etc.

CYPHER WORKING

131. No attempt will be made here to discuss cypher systems, but the effect of radio links on such systems will be briefly considered. If signals are encyphered character by character on a cypher machine and then teleprinted over a radio link subject to noise interference or fading, as soon as a spurious character is injected or a character omitted there will be difficulty in decyphering at the receiving end. If the radio link provides a teleprinting error probability of 1 in 1,000, this difficulty may arise approximately every 3 minutes—a very serious limitation. To provide radio teleprinter links of greater reliability than this is not easy and may indeed be uneconomic. Hence other solutions have been investigated, and it is believed that a reliable one has been found, although the equipment required at present is considerable.

CONCLUSIONS

132. The design and provision of teleprinter radio links are still in their infancy. The facility of direct transmission from a keyboard at one end to a page copy at the distant end is very attractive. However, it introduces new traffic-handling and security problems. The uniformity of line and radio systems would be a big advantage from many points of view.

133. Many aspects of the desirability of the change-over from the morse system to teleprinter working are controversial. In an E.M.E.R. devoted to a description of the teleprinter system it is not possible to consider in detail all the advantages and disadvantages as compared with morse working. Nevertheless there is a steady swing to the teleprinter principle, and with further development there is every possibility that a very reliable system can be produced for cyphered and uncyphered traffic on main links. The suitability of the system for subsidiary links of the mobile field type is not yet established. The wide use of automatic systems will inevitably lead to a reduction in the number of trained morse operators, whereas there will still be a need for manual systems to cover emergencies. This aspect of the problem should not be overlooked.

Analysis of triple frequency group

134. In para. 63 it was stated that the percentage modulation per channel of a multi-channel system must be less than for the single-channel case. If the modulation per tone for N tones is 1/nth of the overload voltage, then overloading will not occur but the level per tone will be low. This level could be increased by suitable phasing as indicated below.

135. Considering a 3-channel system of carrier frequencies f_1, f_2, and f_3, which bear the relations $f_1, = \omega - \triangle\omega$, $f_2 = \omega$ and $f_3 = \omega + \triangle\omega$, the waveform of the resulting signal may be expressed for the case of maximum amplitude, i.e., all frequencies in phase at $t=0$, and for the minimum amplitude case, two components in phase but the third in anti-phase at $t=0$ as in paras. 136 and 137. Intermediate phasing conditions produce amplitude values between these two extremes.

136. The maximum case is shown in Fig. 6(a) for the three components in phase at $t=0$.

Under these conditions the resultant waveform is given by :—

$$A = \sin(\omega - \triangle\omega)t + \sin\,\omega t + \sin\,(\omega + \triangle\omega)t$$

which may be expanded into

$$A = \sin\,\omega t.\ \cos\triangle\omega t - \cos\,\omega t.\ \sin\triangle\omega t + \sin\,\omega t + \sin\,\omega t.\ \cos\triangle\omega t + \cos\,\omega t.\ \sin\triangle\omega t.$$

$$\therefore A = \sin\,\omega t(1 + 2\,\cos\triangle\omega t)$$

which is a normal modulation envelope with a mean frequency of ω and a modulation of $2\,\cos\triangle\omega t$.

137. The minimum case is shown in Fig. 6(b) for two components in phase and the third in anti-phase at $t=0$. Under these conditions the resultant waveform A is given by :—

$$A = \cos\,\omega t + \cos(\omega + \triangle\omega)t - \cos(\omega - \triangle\omega)t$$
$$= \cos\,\omega t + \cos\,\omega t.\ \cos\triangle\omega t - \sin\,\omega t.\ \sin\triangle\omega t$$
$$= \cos\,\omega t\ \cos\triangle\omega t - \sin\,\omega t.\ \sin\triangle\omega t.$$
$$\therefore A = \cos\,\omega t - 2\,\sin\,\omega t.\ \sin\triangle\omega t$$

Suppose expression is of the form $R.\ \cos\,\omega t + S\,\sin\,\omega t$

$= T\,\cos(\omega t + \phi)$ and on expanding this

$= T\,\cos\,\omega t\,\cos\,\phi - T\,\sin\,\omega t\,\sin\,\phi$

or $T\,\cos\,\phi = R = 1$ and $T\,\sin\,\phi = S = 2\,\sin\triangle\omega t$

$\therefore T = R^2 + S^2$ and $\phi = \tan^{-1} S/R$

Then by substituting these values in the expression $A = \cos\,\omega t - 2\,\sin\,\omega t\,\sin\triangle\omega t$, the expression becomes :—

$$A = \sqrt{1 + 4\sin^2\triangle\omega t}\ \cos(\omega t + \tan^{-2}\,2\,\sin\triangle\omega t.)$$

This represents a mean frequency of $f = \omega 2/n$ having phase modulation represented by the term $\tan^{-1}(2\,\sin\triangle\omega t)$ and an envelope represented by the term $\sqrt{1 + 4\,\sin^2\triangle\omega t}$. This envelope is of the form shown in Fig. 6(b). It is to be noted that the envelope peaks at double the frequency of the "inphase" triple frequency group of Fig. 6(a) and that the maximum amplitude has been reduced from 3E to $\sqrt{5}$.E.

138. Two such triple-frequency groups could be combined with a phase relationship, such that the peaks of one envelope fill the troughs in the other, because the period between peaks is the same for triple groups of the same value of $\triangle\omega$, and the resultant combined signal envelope is a slight ripple of the form shown in Fig. 6(c). The maximum amplitude of this ripple is approximately 3.25E.

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Supplementary Note—Since the preparation of this E.M.E.R., certain inter-Service operational nomenclature has been agreed (see Tels. A 307). The main point of interest is that the term "carrier shift" has been abandoned in favour of "frequency shift."

END