WS No. 19 Mark III

Note: This issue supersedes Issue 1, which has been amended throughout.

THE APPLICATION OF MULTI-CHANNEL TELEPHONY EQUIPMENT TO RADIO LINKS

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Issue 2, 16 May 1947
Distribution - Class 800. Codes Nos. 4 and 5

INTRODUCTION

1. Multi-channel radio telephone links are now common in civil practice, especially for services to small islands. The equipment for these services is specifically designed for the task, and a performance almost indistinguishable from line is obtained. A small number of vehicle equipments providing a 6-channel radio telephone service have been used by the British Army. These equipments (known as Wireless set No.26, see Tels. F 320) are representative of early civil practice. A field type of multi-channel equipment (known as the Wireless set No.10, see Tels. F 160) has also been designed during the war.

2. The object of this regulation is to present the technical problems involved in the application of multi-channel telephone equipment to radio links in general. The adaptation of existing Army multi-channel equipment to radio links is also considered.

3. The provision of a multi-channel relay system which uses line where convenient, and radio where line is not so convenient, has great advantages. Some suggestions for the development of such a system are given towards the end of this regulation.

BRIEF DESCRIPTION OF THE ARMY MULTI-CHANNEL LINE EQUIPMENTS

4. The British Army carrier telephone equipments consist primarily of:-
   (a) Apparatus, carrier telephone (1 + 1). (A.C.T. (1 + 1))(see Tels. U 150).
   (b) Apparatus, carrier telephone (1 + 4). (A.C.T. (1 + 4))(see Tels. U 100).

It is only necessary here to give an outline of their principles, before considering the problem of application to radio links.

5. In the A.C.T. (1 + 1), one audio circuit and one carrier circuit are provided. The audio channel is a 2-wire circuit and extends roughly from 0 to 3kc/s. For the carrier circuit, a carrier frequency of 6kc/s is modulated by the speech frequencies; the lower sideband (6 to 3kc/s) is selected for transmission in one direction and the upper sideband (6 to 9kc/s) is used in the opposite direction.

6. Similarly with the A.C.T. (1 + 4), the speech from the four carrier telephones is assembled in the range 3 to 16kc/s (for 4-wire working) and 3 - 35kc/s (for 2-wire working). Each channel occupies a frequency band of roughly 3kc/s. The filters used for the separation of the various channels require a few hundred cycles to develop the necessary cut-off attenuations so that each channel has an effective speech band of approximately 300 to 2,600c/s; this provides reasonable quality circuits quite suitable for multiple tandem connection as in exchange service. The frequency allocations for some typical carrier telephone systems are shown in Fig.1. A block schematic of a (1 + 4) carrier telephone system is shown in Fig.2.

7. This method of providing multi-channel facilities is known as frequency division, as opposed to the time division method (as used in the W.S.10). Frequency division multi-channel is widespread in line practice because it uses the narrowest possible frequency band for the transmission of intelligence. It is not possible to compress speech into a band of less than about 2.5kc/s without subtracting something from the quality or individuality of the speech. Systems are known which employ a narrower frequency band at the expense of individuality, but not necessarily with very much less intelligibility. Thus the type of multi-channel

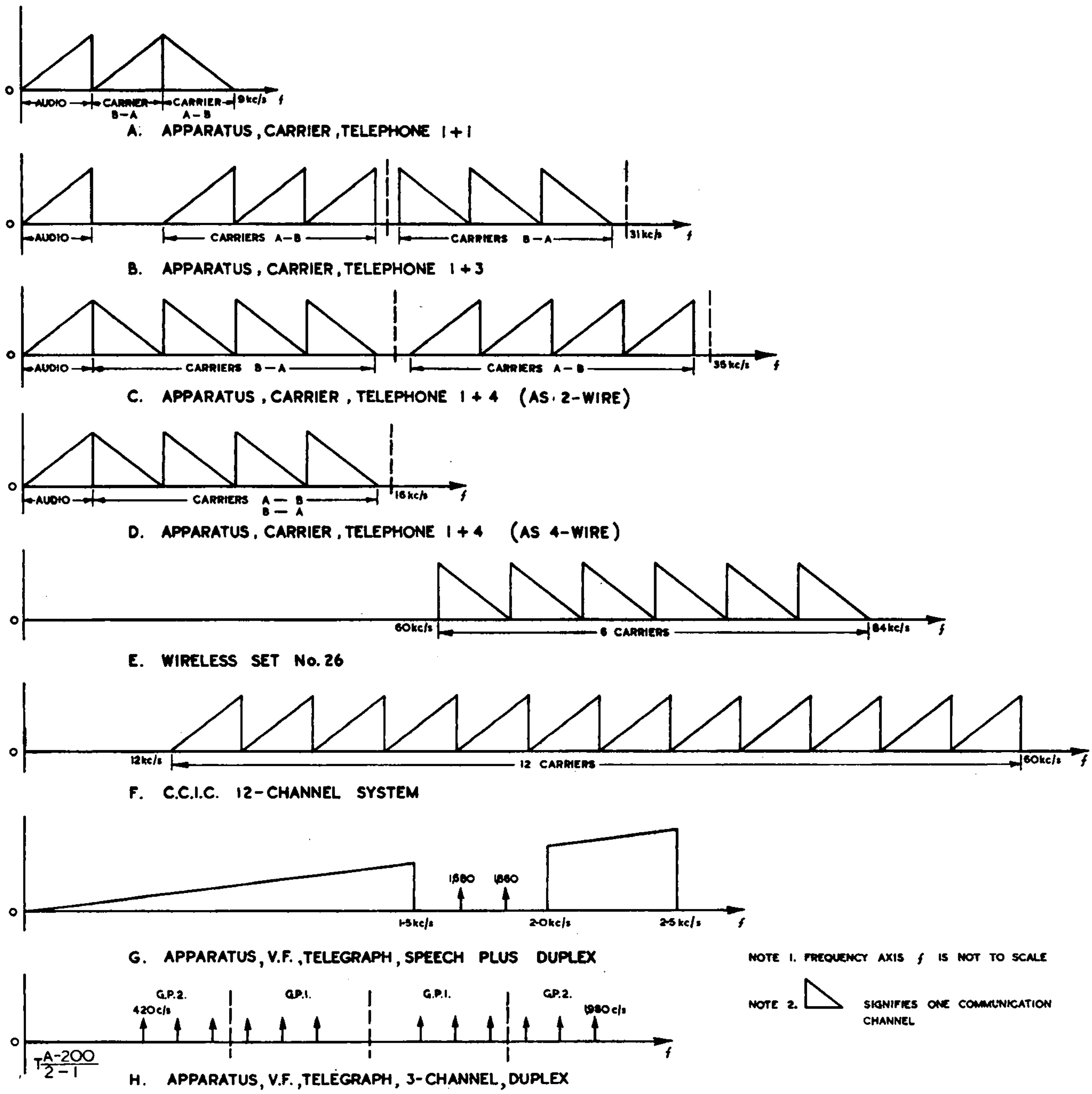

Fig.1 - Allocation of frequencies for multi-channel systems

equipment used in line practice has something to commend its application to radio links, in that it occupies a narrow frequency band in the ether.

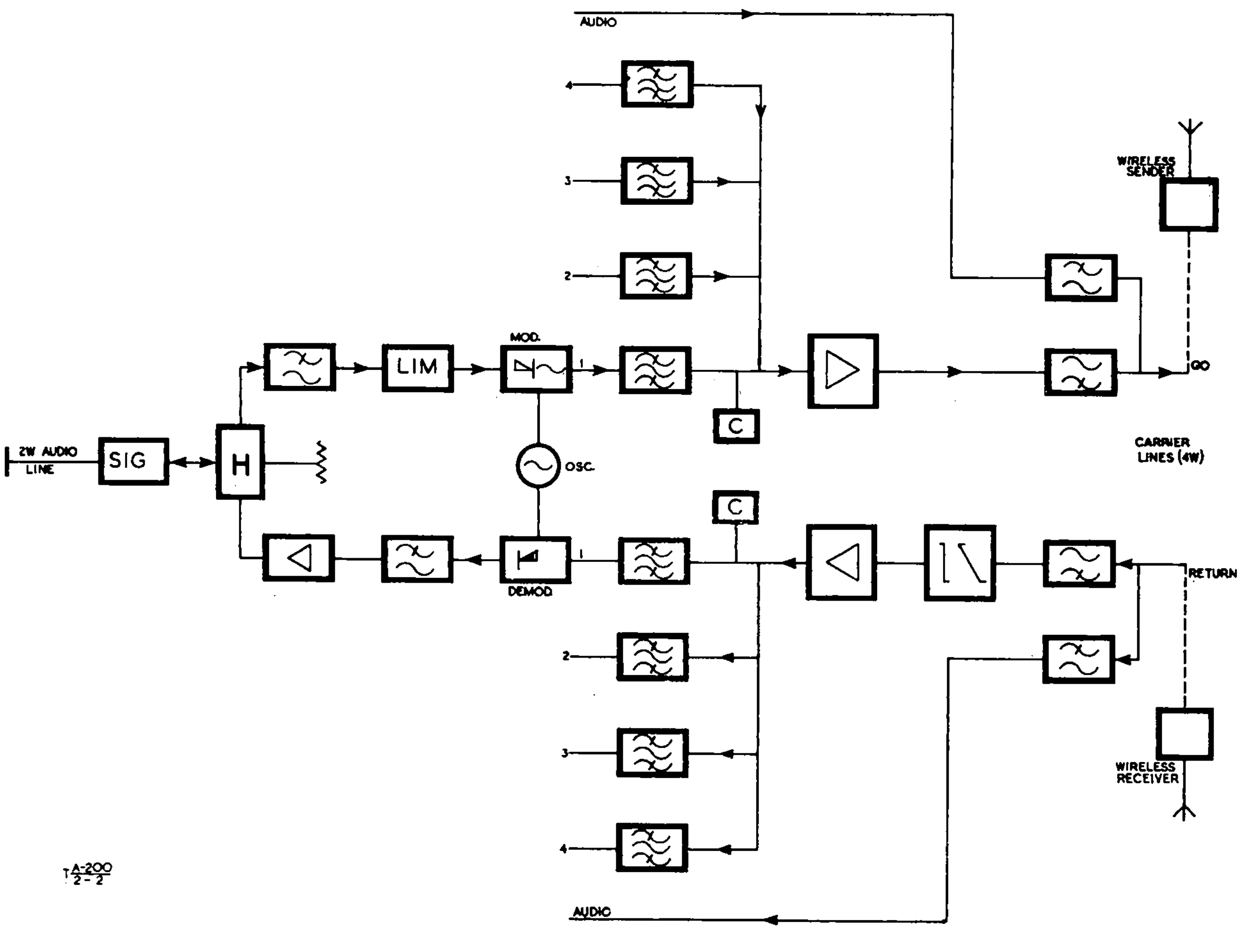

Fig.2 - Block diagram of A.C.T. (1 + 4)

8. The system of modulation used in these line equipments is essentially amplitude modulation with carrier suppression followed by single sideband selection. Thus, with all channels of an A.C.T. (1 + 4) conveying speech in one direction, there are five independent carrier-frequency voltages of complex waveform applied to the carrier line. Periodically, it must happen that the five voltages at these frequencies all add up, producing an instantaneous peak voltage approximately five times the average peak voltage output of one channel.

9. With these general principles in mind, it is possible to pass to a consideration of the characteristics of the radio links to which these equipments can be applied.

GENERAL CONSIDERATION OF CHARACTERISTICS OF RADIO LINKS

10. Consider a unidirectional radio link as a 4-terminal, active, electrical network; the audio-input terminals of the transmitter correspond to the input terminals of the network, and the audio-output terminals of the receiver correspond to the output terminals of the network. The network is active, since it contains several sources of E.M.F., e.g., the various H.T. supplies, noise voltages, etc. The network may have some or all of the following electrical characteristics:-

(a) A certain transfer-voltage-ratio versus frequency characteristic, i.e., a curve of receiver output voltage against frequency, for, say, 1V input at the transmitter.

(b) A corresponding phase/frequency characteristic.

(c) A certain input-voltage versus output-voltage characteristic for each frequency transmitted by the network. If this is not linear over a range up to the overload voltage, then the network will produce harmonics in the output which are not present in the input; it will also cause intermodulation or combination frequencies when two or more independent frequencies are applied to the input.

(d) Voltages at the output which are independent of the input, e.g., noise voltages picked up from the ether or from the equipment.

(e) The output frequency may be displaced from the input frequency by a fixed small amount, e.g., a single sideband radio link with slight "out of synchronism".

(f) The input and output frequencies may differ slightly and in a random manner, e.g., when diverse-path transmission effects exist in the radio link.

(g) Practically all the above characteristics can be variable with time.

REQUIREMENTS OF A RADIO LINK FOR LINE MULTI-CHANNEL OPERATION

General

11. Line multi-channel equipment is designed for a transmission system consisting of a line (possibly with intermediate amplifiers), which has a much more predictable performance than a radio link. Such lines are fairly stable and automatic gain-control features in the line equipment are only necessary on lines of about 500 miles or more. Neither A.C.T. (1 + 1) nor (1 + 4) include automatic gain-control features. In the case of a line, the characteristics (a) to (g) in para. 10 are usually as follows:-

(a) A rising attenuation/frequency characteristic, that is, a falling curve of transfer-voltage-ratio versus frequency. If the line is of the open-wire type, the curve may be "bumpy" above about 10kc/s, due to reflections at irregularities in the line. The curve will vary more or less with weather conditions in the case of open-wire lines, and will vary with temperature in the case of cables and open-wire lines.

(b) The phase/frequency characteristic rises with frequency and is fairly stable.

(c) The input and output voltages of the line alone are linearly related at all frequencies. When amplifiers are in circuit, this is true only up to the overload point of the amplifiers. When loading coils and transformers are in circuit, non-linearities are introduced.

(d) Slight noise voltage, crosstalk or radio interference is possible on lines. Carefully balanced and transposed 2-wire lines keep this to a minimum.

(e) The line system itself cannot cause differing input and output frequencies. If, however, the carrier telephone equipment terminals are not synchronized, the input and output audio frequencies can differ.

(f) In a line system there is no analogy to radio multi-path effects, provided the line is free from irregularities.

(g) Line characteristics can be variable, but to a much less degree than with most radio links.

Amplitude and phase characteristics

12. If a radio link is to give a performance equivalent to that of a line, it must have characteristics no worse than those above. Considering first the transfer-voltage-ratio to frequency characteristic of the radio link; this must be flat or slightly falling over the range 300c/s to 9kc/s for the A.C.T. (1 + 1), and over the range 300c/s to 16kc/s for the A.C.T. (1 + 4). Transmission below 300c/s is not necessary if separate voice-frequency signalling is used in the audio channel. The A.C.T. (1 + 1) includes equalization facilities which can correct for up to a 6db. fall of output voltage from 3kc/s to 9kc/s. The A.C.T. (1 + 4) includes equalization facilities which can correct for up to an 8db. fall from 300c/s to 16kc/s. The over-all attenuation at the highest frequency to be transmitted should not be more than about 20db. Although the line equipment has a gain of about 45db., it is preferable not to use all of this gain if good signal-to-noise ratios are required.

13. The A.C.T. (1 + 1) and (1 + 4) are not sensitive to phase/frequency characteristics and therefore these will not be considered further.

Linearity requirements

14. The linearity requirement (characteristic (c) in para. 11) is perhaps the most difficult to meet with radio links not designed for multi-channel telephony. Average radio equipment is prone to non-linearity due to transmitter modulators, receiver detectors, receiver amplifiers, etc. Line amplifiers are always designed with a large measure of negative feedback to reduce non-linear distortion. Non-linearity in the transmission system causes inter-channel crosstalk. For instance, if we consider a frequency of 1.5kc/s in the audio channel of the A.C.T. (1 + 1), then non-linearity will cause frequencies of 3, 4.5, 6kc/s, etc., to appear in the output. In this instance, the 4.5kc/s is direct interference at 1.5kc/s (6kc/s minus 4.5kc/s) in the carrier channel. Similarly, crosstalk due to harmonics can occur with the A.C.T. (1 + 4). In addition, intermodulation between the frequencies in two separate channels can cause products that fall in other channels. Thus, two frequencies f1 and f2 can cause second-order products (f1 ± f2), third-order products ($2f_1 \pm f_2$ and $f_1 \pm 2f_2$) and higher products. More detailed information on this subject is given by Brockbank and Wass. (see Bibliography, sub-para. 78(d)).

15. One method of reducing crosstalk interference due to non-linearity is to use multi-channel modulating equipment which translates the speech channels into an octave band. For example, if six speech channels are assembled in the band 60 to 84kc/s, any harmonics of, say, 61kc/s would fall outside the band and thus not cause interference or crosstalk. This is, in fact, the method employed in the No.26 set. Such a method can be used with the A.C.T. (1 + 4) since it contains a group-modulation facility which translates the four carrier channels into the range 19 to 32kc/s, which is an octave group. Thus, in a radio link that would handle 19 to 32kc/s, interference from this cause would not be such a serious problem. This does not mean that non-linearity is unimportant, because two or more channel frequencies can still cause intermodulation products which will interfere. However, the octave-group method does place a somewhat less stringent requirement on the linearity of the link. It should be noted that it requires a greater band-width in the radio equipment.

Noise consideration and modulation per channel

16. Passing next to a consideration of noise, civil line practice requires signal-to-noise ratios in each speech channel of 60 to 70db. for one link, whilst in Army

lines of communication practice, figures of about 50db. have been considered to be the satisfactory minimum. For one channel over a radio link, a figure of 45db. might be taken as a reasonable minimum if numbers of such links are not to be connected in tandem. As radio technique improves, figures of 70db. should, however, be aimed at.

17. Care must be taken in correlating these figures to the signal-to-noise ratio of the radio link itself, since the percentage of modulation must be taken into account. The average percentage modulation per channel of the radio carrier, whether A.M. or F.M., must be considerably less than 100% because the instantaneous voltages from each channel of the carrier equipment are additive. If the total instantaneous voltage exceeds that corresponding to 100% modulation, overloading occurs and this is bound to produce intermodulation and inter-channel crosstalk to a greater or lesser extent, depending on the overload characteristic of the system. The actual percentage modulation to be allotted to each channel is dependent upon several factors of which the following are the most important:-

(a) Telephone sensitivity
(b) The distribution of talker volumes and local line losses.
(c) The ratio of peak voltage to average R.M.S. voltage in each channel.
(d) The active or engaged time per channel.
(e) The permitted probability of overmodulating.

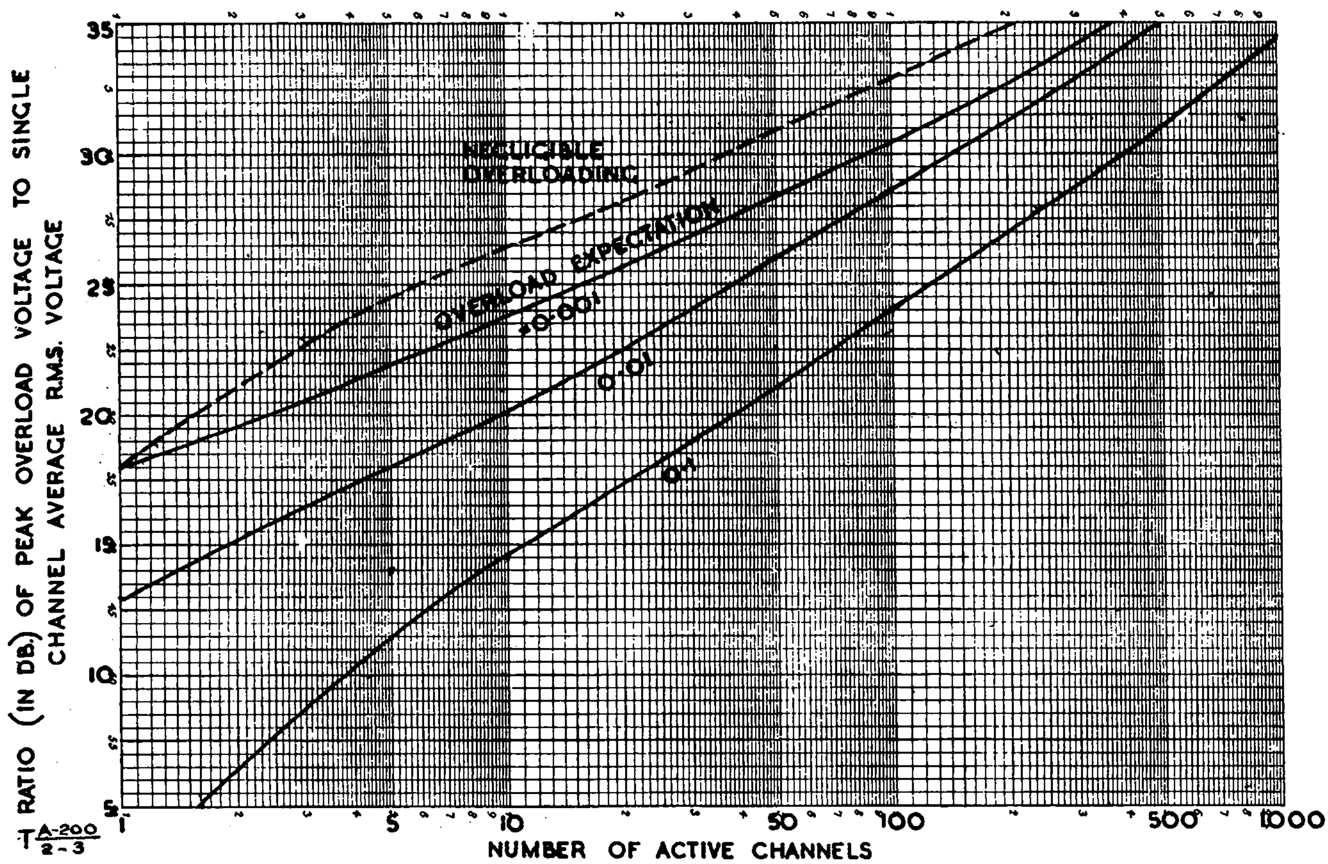

Fig.3 - Multi-channel network characteristics

18. This problem is similar to the design of a multi-channel amplifier or other similar common equipment having an overload point. For a fuller treatment of the problem, reference should be made to Holbrook and Dixon, and Brockbank and Wass, (see Bibliography, sub-paras. 78(c) and (d)). One of the curves given in the former paper is reproduced in this regulation as Fig.3 since it is of wide and useful application.

19. If the average R.M.S. voltage in each channel is regulated to a fixed level (i.e., factors (a) and (b) of para. 17 are ignored), then the probability of the peaks of speech voltage exceeding various levels depends only on the nature of the speech. If gramophone records of conversational matter are analysed and measured, it is possible to prepare graphs of probability against overload voltage. Furthermore, if several records representing several channels are combined and re-recorded, an analysis of this record gives the probability of various peak voltages being exceeded for several channels. Actually, this should be carried out with each channel transposed into its correct carrier-frequency location, but little error results from an audio-frequency combination. The latter has actually been carried out by the Bell Telephone Laboratories, and Fig.3 is a reproduction of the results as given in the paper by Holbrook and Dixon. It shows the peak overload voltage, expressed in db. above the average R.M.S. channel level, for various numbers of active channels for probabilities of overloading of 0.1, 0.01, 0.001 and negligible. Reference to the curve for a probability of overloading of 0.01 shows that for five channels the peak overload level is 18db. above the average channel R.M.S. voltage, while for 50 channels it is another 8 db. higher.

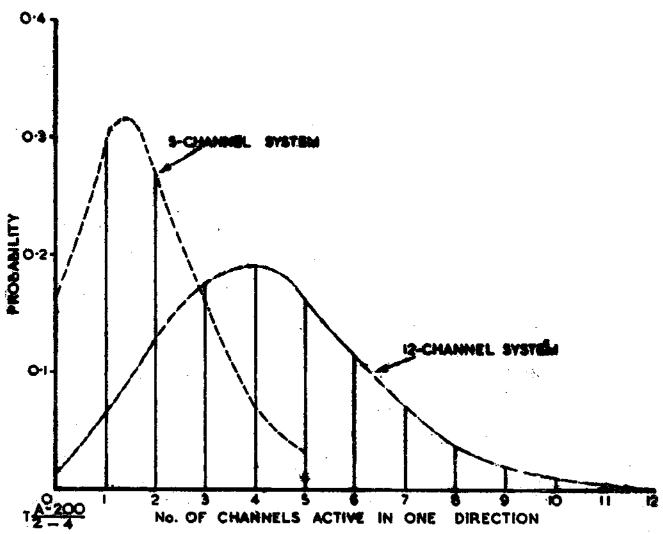

Fig.4 - Probability of various numbers of channels being active in 5-and 12-channel systems

20. These curves still do not represent the practical case, since all channels of a system are rarely engaged simultaneously, that is, factor (d) of para. 17 must be taken into account. Suppose that each speech channel carries 0.7 traffic units (i.e., the circuit is engaged for 0.7 of the busy hour - a fairly representative figure) and that the probability of speech passing in the direction considered is 0.5, then 0.35 is the probability that any one channel is active. The probabilities for various numbers of channels being active can then be deduced approximately, using the Erlang or Poisson formulae. These probabilities, fora5-channel system and a 12-channel system carrying 0.35 traffic units in each direction per channel, are shown by way of example in Fig.4 which is based upon the Erlang formula.

21. To calculate the probability of the peak voltage exceeding a given overload point, it is now necessary to assume various numbers of channels engaged, and deduce the probability of overloading in each case from Fig.3. The sum of the

products of this probability and the probability of that number of circuits engaged, gives the average probability of overloading for the system. For example, consider a 12-channel system with an overload peak voltage of 20db. above the channel average R.M.S. voltage. Then when six channels are engaged (probability of 0.115), the probability of overloading is, by interpolation from Fig.3, about 0.005. The probability of six channels overloading is, therefore, given by the product 0.115 x 0.005 = 0.00057. This is repeated for all other numbers of channels engaged and the probabilities are added to give the over-all average probability of overloading.

22. This is a somewhat tedious process, and for systems of five or more channels an approximate answer to the problem may be obtained by entering Fig.3, using the average or most probable number of active channels. The latter is simply the total number of channels multiplied by the probability of any one channel being active, i.e., 0.35n for the above traffic on an "n"-channel system. For systems of fewer than five channels, an approximate answer may be obtained by assuming all channels always active.

23. For a channel active probability of 0.35, the average number of active channels in a 5-channel system is 1.75 and in a 50-channel system 17.5. From Fig.3, for an overloading probability of 0.01, the peak overload levels are approximately 15 and 22db. respectively above the channel R.M.S. level. That is, an increase in load capacity of 7db. permits an additional 45 channels to be operated. This is a useful feature of multi-channel radio circuits of this type.

24. An overload probability of 0.001 is more usual for line equipment, but a relaxation of this figure to 0.01 is considered permissible where load capacity is a prime consideration. The latter figure will be assumed in the following consideration of noise. A channel active probability of 0.35 will also be assumed.

25. From Fig.3, remembering that the peak overload voltage is 3db. above the R.M.S. load capacity, we may deduce that, for a 5-channel system, each channel should operate on an average at a level of 12db. below the level which just causes overloading. If the latter is taken to be 100% modulation, then this represents an average modulation of 25% per channel. Hence, to meet the suggested noise requirements, the radio link must provide a signal-to-noise ratio of at least 45db. when measured at 25% modulation and on a 3kc/s band-width. Alternatively, the signal-to-noise ratio on the full bandwidth of 16kc/s for 100% modulation should be no worse than 50db., and similarly for 50 channels the signal-to-total-noise ratio with 100% modulation should be 47db., i.e., a few decibels better than the channel signal-to-noise ratio. The channel limiters (see para. 40) serve to prevent the modulation per channel from reaching excessive values. With F.M. systems, where the noise per kc/s of band-width depends upon the modulating frequency, other considerations apply, and it may be necessary to allow higher deviations per channel for the upper channels.

Frequency difference effects

26. Characteristic (e) of para. 10 is found only in single sideband radio links. For speech, an overall tolerance of ± 25c/s is permissible, whilst for V.F. telegraphs ± 6c/s is preferable but ± 12c/s is permissible. It must be remembered that some of this tolerance is required for the multi-channel equipment itself, so that the restriction on the radio equipment may be very severe.

27. Characteristic (f) of para. 10, namely, differing input and output frequencies due to multi-path transmission effects, is associated only with long circuits of, say, 500 miles and over. Its effects appear as distortion in audio-frequency links and distortion and intermodulation in multi-channel links. These effects are very difficult to mitigate. The use of diversity-receiving aerials and steerable aerial systems has been the most successful means of minimizing these effects. Single sideband radio also offers advantages for such links, since the phase of the carrier is unimportant.

Stability

28. Characteristic (g) of para. 10, namely, variability of performance of the radio link (i.e., general and selective fading), is the next most serious problem.

29. The radio equipment must have the most efficient possible A.G.C. system to cope with general fading. Selective fading is a more difficult problem where multi-channel operation is concerned. If the carrier telephone channels are to be lined up for switchboard use with, say, a 3db. over-all equivalent, then the radio link must be very stable. For suppose a selective fade occurs which affects the radio carrier but not the sidebands (which may be 16kc/s or more away), the A.G.C. increases the I.F. amplifier gain and, if this rises more than about 3db. above the gain during lining-up, then the telephone circuits will sing and be momentarily unusable. Similarly, a fade of the sidebands would be outside the scope of the A.G.C. and a rise of carrier-channel attenuation would result. Such occurrences would be objectionable to the talker and may cause non-operation of the V.F. ringers. We see here a special advantage of a frequency-modulated (F.M.) radio carrier. In the case of an F.M. link, the output voltage from the receiver for a given fixed input voltage to the transmitter is a function of the deviation, and is independent of the received carrier amplitude (provided it is above the threshold value). That is, the modulator which causes the deviation, and the discriminator which detects it, are the factors which control the over-all transfer voltage frequency characteristics. Both the modulator and the discriminator may be made stable so that the whole link is very stable. For reliable operation, the radio link stability measured at L.F. should be no worse than ± 1db. over any 24 hour period.

30. In view of all the above difficulties, present practice for multi-channel radio (excepting U.H.F. radio) is therefore the octave group principle in combination with F.M. radio links. However, it is possible that developments in radio technique will be such that octave group working is not essential, and correspondingly larger groups of circuits may be applied to one radio link.

CONSIDERATIONS GOVERNING CHOICE OF RADIO-FREQUENCY BAND

31. The considerations governing choice of frequency band are numerous. Firstly, the range must be considered. For ranges above 100 miles, frequencies below 20Mc/s must be employed. Below 20Mc/s the use of F.M. may not be a practicable proposition for multi-channel telephony on account of band-width problems. Even with A.M., the band-width (32kc/s for the A.C.T. (1 + 4)) may be too great for general adoption. The use of single sideband radio is therefore indicated for long-distance multi-channel telephony using frequencies below 20Mc/s.

32. For ranges less than 100 miles, there is considerable scope for systems using frequencies above 20Mc/s. Here F.M. may be employed and good stable circuits obtained. In the U.H.F. band there is also ample scope for multi-channel systems

with large groups of circuits using pulse or frequency modulation. Such systems should preferably accept the full band of carrier frequencies from a line, and should not necessitate bringing all channels down to audio frequency.

OTHER REQUIREMENTS FOR THE RADIO AND LINE EQUIPMENT

Duplex operation

33. The radio link must be duplex, i.e., a transmitter and receiver must work continuously at each terminal site. Different radio frequencies must be used for each direction of transmission, and the receiver must not be blocked by the transmitter. The sending and receiving aerials should be directional and erected to give the maximum possible attenuation between aerials. Preferably, the transmitter and receiver site should be widely separated and the 4-wire circuits completed by a carrier-frequency telephone cable. The line equipment must be used in the 4-wire condition, i.e., separate go and return paths.

Continuous operation

34. The radio equipment must be capable of continuous operation. Wireless sets designed for send-receive switch working are rarely suitable for the function considered in this report. The line equipment is normally designed for continuous operation and will not give trouble on this score.

Radio interference

35. The line equipment embodies items such as vibrators, relays, etc., which generate radio interference. The equipment could be installed at a remote point and connected to the radio equipment by a carrier-frequency quad cable, but this may be a serious restriction and it is therefore necessary to suppress the offending items. The relays and ringing vibrator can be suppressed by simple resistance-capacitance networks. The power vibrator, if used, is a more serious problem, especially if radio frequencies of 20-50Mc/s are used. Mains operation of the line equipments is therefore to be preferred.

I.F. band-width

36. If the radio system is A.M., then the receiver I.F. must be wide enough to pass the desired band, i.e., characteristic (a) of para. 10 must be reasonable. For the A.C.T. (1 + 1), the I.F. should be about 25kc/s wide for 6db. down, and for the A.C.T. (1 + 4), it should be 40kc/s. These figures are somewhat liberal in comparison with the highest modulation frequencies to be transmitted (9kc/s for the A.C.T. (1 + 1) and 16kc/s for the A.C.T. (1 + 4)). This is done purposely, however. If the I.F. attenuation curve is starting to bend upwards at, say, + 16kc/s, then small oscillator drifts or slight mistuning will seriously affect the attenuation of the top channel of the A.C.T. (1 + 4) using frequencies of 13 - 16kc/s.

37. If the system is F.M., then the I.F. band-width will be determined by the deviation necessary to meet the signal-to-noise requirements.

Exchange service

38. When the telephone channels described in this regulation are terminated on switchboards, care must be taken to ensure that the radio equipment receives a level of speech sufficient to ensure an adequate percentage of modulation. This means that

connections should not be set up involving other circuits of transmission equivalent greater than about 10db. at each end of the radio trunk circuit. This condition is no different from the usual problem of a large switched network, except that the radio link usually contributes the most noise, and may be blamed for a bad circuit, which is nevertheless due to the line loss.

39. This is largely a question of transmission network planning, and provided the radio link is nearly as good as the zero db. level lines and the network is carefully planned, no special instructions at the switchboard are necessary.

Signalling

40. The carrier telephone equipment will be provided with some type of V.F. signalling in each channel. No difficulty will be experienced in the operation of these ringers over the radio equipment, provided the channels conform to the standard suggested in the foregoing sections. In the case of V.F. signalling systems which involve the continuous transmission of tones in each channel, due allowance must be made when calculating modulation per channel.

Channel limiting

41. It is usual to provide channel limiters on multi-channel equipment to prevent the carrier-frequency level per channel from exceeding a known figure. It is also desirable that this limiting effect should be used when the multi-channel equipment operates over a radio link, so that the percentage modulation per channel does not exceed a known figure. In the A.C.T. (1 + 4), the lining-up level at the channel audio-input terminals is 0dbm. and the overload level approximately +5dbm. Similar figures apply to the A.C.T. (1 + 1).

BRIEF DESCRIPTION OF EXISTING ARMY MULTI-CHANNEL SETS

The Wireless set No.26

42. This set provides a 6-channel radio telephone link. One terminal station consists of two vehicles with power trailers. One vehicle houses the transmitter and the other the receiver and multi-channel equipment.

43. The speech from the six telephone channels is assembled in the frequency range 60 to 84kc/s, using a 4kc/s spacing. This is carried out by modulating carrier frequencies of 64, 68 to 84kc/s with the six speech bands, and selecting the lower sidebands by means of crystal filters. The combined output of these filters is within an octave group, and is supplied to the transmitter modulator for transmission over the radio link.

44. On the receiving side, the 60 to 84kc/s output of the radio receiver is fed to a similar set of filters which separates the six channels. The filter outputs are demodulated by the same oscillators and fed via a hybrid transformer to the 2-wire telephone lines. V.F. ringers are provided.

45. The radio transmitter employs amplitude modulation and transmits a mean power of 65 to 100W in the frequency range 85 to 100Mc/s. At a speech level of 0dbm., the depth of modulation of the transmitter is approximately 20% per channel. Thus the transmitter radiates a carrier and two sets of sidebands, one set between 60 and 84kc/s below the carrier and a similar set above the carrier. The radio receiver has an I.F. at 3Mc/s of 320kc/s width and requires an R.F. input of about

1mV to give good quality audio circuits. The equipment has Koomans aerial arrays and the range is essentially visual.

The Wireless set No.10, Mk.1

46. This set provides an 8-channel radio link, using pulse-modulated centimetric radio. The eight channels are derived by the use of the time-division multiplex principle. It is not the purpose of this regulation to discuss the system in detail, but a brief description of the general principles is given for the sake of completeness.

47. Pulses of centimetric radio are transmitted from the sending site to the receiving site. Every ninth pulse is arranged to synchronize the sending and receiving equipments. The eight pulses between synchronizing pulses are allotted in turn to the eight channels. The audio-frequency intelligence in each channel suitably modulates the appropriate pulse. The pulses may be modulated in amplitude, width, phase or by other means. The received pulses are demodulated, and by virtue of the synchronism, the audio-frequency energy is delivered to the appropriate channels.

48. Up to the present time, it has not been found practicable to apply this type of multi-channel working to lines. Firstly, the band-width required is several times that of conventional single sideband systems. Secondly, the inevitable electrical irregularities that occur in practical lines cause reflection of pulses and consequent crosstalk. Thirdly, distortion of pulses, due to the fact that different frequencies are propagated with different velocities, causes inter-channel crosstalk. Although with ideal lines it is possible to develop a pulse-modulated line system, it is doubtful whether it would ever provide circuits of such high quality as existing line systems.

49. Hence, it is only possible to connect eight audio-frequency lines to the No.10 set. If these eight channels are delivered to the radio set by a carrier-frequency line, it is necessary to instal carrier equipment to derive the eight audio circuits. This is a disadvantage, since it involves much additional equipment and causes a slight reduction of signal-to-noise ratio.

50. It is possible to conceive a pulse-modulated radio link which will accept carrier frequencies direct from a line. Thus, a single-channel, pulse-modulated link capable of transmitting frequencies of 300c/s to 35kc/s and having good linearity and noise characteristics, would be capable of accepting the carrier frequencies from two A.C.T. (1 + 4) systems. Such a radio link would be suitable for bridging gaps in a line, at water barriers, for example, without the necessity of dropping to audio frequency at each radio site. This system is to be used in the WS.10, Mk.2.

51. However, multi-channel practice is tending towards larger and larger groups of circuits. In civil practice, coaxial lines having groups of 660 circuits are being employed. It seems desirable, therefore, to concentrate upon radio links capable of accepting still larger blocks of circuits. The conventional A.M. type of link described in the previous section can be evolved to employ the minimum band-width in the ether. The pulse modulation system requires a much greater band-width, although the power transmitted may be very small. The pulse system has other advantages especially for military use.

52. It is difficult at the present stage of development to see which system will offer the best features for military use. It seems almost certain that U.H.F.

radio, with pulse or frequency modulation, will be a serious competitor of line systems in the future. The problem of providing many channels between radio site and switchboard can, no doubt, be solved by keeping the distance small and using coaxial cable, with the pulse equipment adjacent to the switchboard.

53. For civil use, it is probable that development will concentrate upon F.M. links capable of accepting modulating frequencies up to 500kc/s. Such links can be fed directly by the carrier frequencies from multi-channel lines.

BRIEF DESCRIPTION OF EXPERIMENTS WITH LINE EQUIPMENT APPLIED TO RADIO LINKS

Experiments with the use of the A.C.T. (1 + 4) on F.M. radio links

54. As stated in the introduction, tests have been carried out during the war on the application of the A.C.Ts. (1 + 1) and (1 + 4) to radio links. The detailed results are given in S.R.D.E. Report 938.

55. The radio sets chosen were American Signal Corps radio sets Nos. 508 and 608. These sets were chosen for reasons of availability rather than exact suitability. They are frequency-modulated sets, covering the band 20 to 40Mc/s, and were designed for audio-frequency simplex working between fighting vehicles. The nominal power is 25W, and the experiments included the use of R.F. amplifiers to increase the output to 250W. The sets had firstly to be adapted for continuous duplex operation. This involved changing the power supplies as the sets were not continuously rated.

56. The sender was crystal-controlled, but the receiver was not, and no automatic frequency-control was provided. The sender and receiver were mounted in the same vehicle and inverted V-aerials were used, spaced at about 80yd. It was found that the choice of sending and receiving frequencies was strictly limited, due to blocking of the receiver by the transmitter and by radiation from the transmitter crystal-multiplying circuits.

57. The L.F. response from transmitter input to receiver output had then to be improved to be reasonably flat up to 16kc/s to accept the A.C.T. (1 + 4) in the 4-wire condition. This was effected by the use of a specially designed adaptor containing a new modulator amplifier and a new demodulator amplifier.

58. When the link had been fully conditioned for carrier working, the A.C.T. (1 + 4) was applied and a field trial carried out. The channel noise was of the random shot effect type and its level was approximately - 30dbm. unweighted, which is not suitable for switchboard use or tandem connection. The stability of the circuits when once lined up was found to be exceedingly good. The transmission equivalent of the circuits did not drift more than ± 0.5db. during 24 hours. This was one of the most striking results of the trial and is attributable to the use of F.M. as pointed out in para. 28.

59. The tests showed that the radio equipment specified was not suitable for multi-channel telephony. Indeed, they proved that the only type of link likely to be suitable for the task is one specially designed for the purpose. The tests did, however, draw attention to some of the advantages and disadvantages of F.M. working.

Operation of speech plus duplex telegraphy equipment over radio links

60. An item of line equipment known as Apparatus, V.F., telegraph, speech plus duplex (see Tels. U 260) is in very wide use in the Army for providing one speech

and one duplex teleprinter channel over a 2-wire audio-frequency line. It provides the two channels by dividing the audio-frequency band into 0 to 1,500c/s for speech and 1,500 to 2,000c/s for V.F. telegraphy. If the transmission system transmits frequencies above 2,000c/s, this band is available for any of the speech harmonics that exist. This separation into bands is carried out by inductance-capacitance filters. The equipment contains a voice-frequency ringer for signalling on the telephone circuit.

61. Since this equipment needs an audio-frequency band only, it might be thought that it could be successfully applied to any existing radio link in order to obtain two channels. Experience up to date, however, has been the reverse, especially with amplitude-modulated radio. Most of the considerations given in paras. 11 and 32 -40 need to be taken into account. In particular, characteristic 11(c) should be good. Suppose this characteristic is not good, i.e., the link has non-linear distortion, then a speech component of, say, 560c/s will, in course of transmission through the radio equipment, be delivered to the line equipment with harmonics of 1,120 and 1,680c/s. The latter is one of the telegraph frequencies, and it will probably disturb the teleprinters, causing printing errors. Similarly, the stability of the link must be good, to allow it to be worked duplex with hybrid transformers.

62. One radio link which has been found partially successful is that consisting of a Radio transmitter BC610E and a Reception set R208 using A.M. at frequencies of 26 to 35Mc/s. The telephone and telegraph circuits thus obtained are not in general sufficiently stable for exchange service.

Operation of V.F. telegraph equipment over radio links

63. Army V.F. telegraph equipment, intended primarily for use over lines, employs a different single audio frequency for each channel. Six duplex channels may be provided over a 2-wire audio circuit or twelve duplex channels over a 4-wire audio circuit. The tone in a channel is interrupted to send teleprinter or other telegraph signals. The idle condition of a channel is the transmission of tone to line. When all channels are idle, the tone voltages may add instantaneously to produce large voltages. This is a similar problem to that discussed in paras. 14 and 15. Overloading in the audio channel would be liable to produce interference between channels.

64. The tone frequencies are chosen to minimize such interference, odd harmonics of 60c/s commencing at 420c/s being used. The spacing between channels is therefore 120c/s. Even harmonics of lower channels thus fall midway between higher channels and reduce the possibility of interference. Odd harmonics of some of the channels do in fact interfere with some of the higher channels. When the lower channels are modulated by telegraph signals, harmonics of the sidebands can also interfere with higher channels.

65. The problem of employing this equipment over radio channels is very similar to that of the speech plus duplex equipment. The factors of non-linearity, noise and stability have again to be considered. The non-linearity requirement is not quite so severe with this equipment. A link giving harmonic products not worse than 25db. below the fundamental (at channel level) will, in general, be quite satisfactory from this point of view.

66. The noise requirements are roughly a signal-to-noise ratio of not worse than 20db. at the output of the telegraph receiving filters. These filters are

approximately 100c/s wide. Taking the audio channel as 2,400c/s wide, this requires a signal-to-noise ratio measured on the audio band-width of $(20 - 10 \log \frac{2400}{100})$ 6db.

This is, however, measured at the telegraph tone level. For six channels this is about 12db. below 100% modulation, and for twelve channels it is about 17db. below 100% modulation. Thus the signal-to-noise ratio of the audio channel at 100% modulation must be at least 18db. for six channels and 23db. for twelve channels. These considerations are somewhat approximate and only apply to random noise. Better figures would be necessary with impulsive noise. It should be noted that the V.F. telegraph filters are relatively narrow (100c/s). If the radio link of the carrier equipment applied to the radio link is of the single sideband type without close frequency control, then frequency-difference troubles will arise. The maximum frequency difference which the V.F. equipment can tolerate is ± 12c/s, although a better design figure is ± 6c/s.

67. A radio link for V.F. telegraph equipment of the present Army type would need to be stable and not subject to quick fading. The equipment has automatic gain-control in each tone channel, but since it is primarily for line use, the time-constant is very long (of the order of 20 to 30sec.).

68. Six-channel V.F. telegraphs have been applied to one channel of the No.10 set with considerable success. There is no reason why the whole twelve channels should not be derived. Thus the complete radio link would provide in this case seven speech and twelve duplex telegraph circuits.

69. In general, a radio link that provides one or more audio channels which are of sufficient quality for switchboard use and are free from frequency-difference effects, is quite suitable for V.F. telegraphy. Actually, the use of two tones per telegraph channel permits of satisfactory working in channels with worse characteristics than those suggested in this section. Equipment of the 2-tone type with quick A.G.C. characteristics is in use in most Army signals organizations. The general problem of teleprinter working over radio is considered in Tels. A 172. It has many features in common with the multi-channel telephony case.

PRIVACY AND SECRECY

70. It is appropriate at this stage to mention the privacy and secrecy of the systems discussed in this report. By privacy is meant the ability of the system to pass intelligence in such a way that persons without special equipment are unable to intercept the messages. By secrecy is meant the ability of the system to pass intelligence in such a way that unauthorized persons, even with special equipment (including equipment similar to that used in the system), are unable to intercept the messages. Both terms are relative, that is, systems may have varying degrees of privacy or secrecy. The privacy of a system can be almost complete, i.e., the eavesdropper with no special knowledge or equipment is unable to extract any intelligence. The secrecy of a system can also be so high that it is, for all practical purposes, complete, especially if random codes are used.

71. It is evident that none of the systems described in this regulation has secrecy. They have, however, varying degrees of privacy. The No.10 set, for instance, has almost complete privacy.

72. The radio link of the No.26 set would not have a very high degree of privacy. Assuming the eavesdropper (without special equipment) had a radio receiver appropriate to the frequency band with a beat oscillator, and that he was suitably located with regard to the transmitter, then he could probably extract a large proportion of the intelligence from the channels. This radio set does, however, lend itself to

channel-switching privacy, i.e., interchanging of channels every two seconds, say. This method provides a good standard of privacy.

73. The radio link provided by the A.C.T. (1 + 1) or (1 + 4) operating over a F.M. radio link would, likewise, not have a very high degree of privacy. The eavesdropper, with an appropriate type of receiver and a beat oscillator, could undoubtedly extract the intelligence.

74. Thus radio equipment, using pulse modulation at centimetric or decimetric wavelengths, has very definite advantages over other systems on the score of privacy.

75. All V.H.F. and U.H.F. systems have the advantage that with directional aerials the coverage is relatively small. Long-distance multi-channel systems must, of necessity, use the H.F. band and they are therefore prone to interception.

CONCLUSIONS

76. The facility of being able to set up long multi-channel telephone circuits on a relay basis, i.e., using line where convenient and radio where line is inconvenient or impracticable, is a very attractive one. It has been developed by the United States armed forces (Radio equipment AN/TRC5) and to some extent by the late German Army (DMG3G, which provides nine speech channels or 27 teleprinter channels). It has not yet been fully exploited and considerable attention is likely to be given to such systems and methods of integrating the line and radio systems evolved.

77. This regulation is intended to draw attention to some of the problems involved in such developments. It cannot be considered as comprehensive on account of the diverse radio and line problems involved. However, it is hoped that the information will be of some value.

BIBLIOGRAPHY

78. (a) S.R.D.E. Report No.938 - Application of multi-channel carrier telephone systems to radio links.
(b) S.R.D.E. Report No.886 - Operation of V.F. telegraph equipment on single sideband carrier systems.
(c) Holbrook and Dixon - Load rating theory for multi-channel amplifiers. Bell System Technical Journal, 1939, No.18, p. 264.
(d) Brockbank and Wass - Non-linear distortion in transmission systems. Part III, I.E.E. Journal, March 1945.
(e) Wireless set No.26, Tels. F 320 - 324.
(f) Wireless set No.10, Tels. F 160 - 164.
(g) Apparatus, carrier, telephone (1 + 1), Tels. U 150 - 154.
(h) Apparatus, carrier, telephone (1 + 4), Tels. U 100 - 104
(j) Apparatus, V.F. telegraph (S + Dx), Tels. U 260 - 264.
(k) Apparatus, V.F. telegraph, 3-channel, duplex, Tels. U 220 - 224.

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