THE FADING MACHINE, AND ITS USE FOR THE INVESTIGATION OF THE EFFECTS OF FREQUENCY-SELECTIVE FADING*

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SUMMARY

The function of the fading machine is to simulate the frequency-selective fading which is characteristic of long-distance short-wave radio channels. Fading of this type is usually due to interference between waves which have traversed multiple paths between sender and receiver, and its effect is often to produce distortion of the modulation of radio waves. Many radio transmission systems have been devised with the object of minimizing the effects of selective fading; the fading machine enables such systems and an ionospheric fade to be compared in the laboratory under precisely controlled fading conditions. The equipment described in the paper incorporates three transmission paths, the group time-delay differences between which may be varied in steps from 0 to 2 milliseconds. The phase differences between the paths may be varied manually ("static" fading) or continuously ("dynamic" fading), with fading rates ranging from 0-1 to 10 fades per second. Random noise, either fading or non-fading, may be included so as to synthesize a complete short-wave radio channel. The fading machine may also be used to simulate diversity reception obtained by spaced aerials. Examples are given of the use of the equipment to assess the merits of double-sideband, single-sideband and frequency-modulated transmission systems with telephony or telegraphy modulation, under conditions of severe selective fading and high noise level.

(1) INTRODUCTION

It is well known that long-distance radio circuits exhibit to greater or less degree the phenomenon of selective fading, i.e. effects due to interference between two or more waves which originate from the same source but traverse different paths between transmitter and receiver and which have, in general, different time delays. Selective fading is probably most marked at high frequencies (short-wave band); the multiple paths in such cases may arise from the simultaneous existence of paths with one and two or more hops between a layer (or layers) of the ionosphere and earth, as shown in Fig. 1.

Fig. 1.—Multiple-path transmission via the ionosphere.

Selective fading effects may also occur at medium frequencies (medium-wave band), sometimes as a result of interference between a ground wave and an ionospherically-reflected wave. At very high frequencies multiple-path conditions may arise as a result of reflections from hillsides, buildings, aircraft or even from temperature inversions in the troposphere.

When selective fading is present, the transmission characteristic of a radio channel is modified so that one or more minima may appear in the attenuation/frequency response, and the phase/frequency response is no longer linear but exhibits steps. The minima usually vary in their location on the frequency scale; in the case of short-wave radio channels the change from a maximum to a minimum at a given frequency may take place in a second or less. In addition to modifying the attenuation/frequency characteristics of the propagation medium, it is possible for selective fading to give rise to severe non-linear distortion of the received signal, i.e. production of harmonics and intermodulation products of the components of the original modulating signal. The nature of the distortion depends on the type of modulation employed, i.e. double- or single-sideband amplitude modulation, frequency or phase modulation.

It is evident that the phenomenon of selective fading is widespread, and experience shows that its effects may be such as to mar seriously the quality of radio links. Considerable attention has been devoted to methods for minimizing the effects of selective fading, e.g. steerable receiving aerials, single-sideband operation, diversity reception, frequency-shift operation for telegraphy and frequency-modulated sub-carrier for facsimile, but it has not often been possible in the past to compare different systems under identical and specified fading conditions except by side-by-side comparisons in the field. Field trials are often expensive and difficult to arrange, particularly when long-distance radio circuits have to be set up. Moreover, the tests must extend over considerable periods of time if a really comprehensive range of fading conditions is to be encountered; there is also the difficulty that the fading conditions in field tests are often unknown, and cannot be specified or repeated accurately so as to permit of reliable comparisons between different receiving or transmitting systems at different times.

The fading machine enables the difficulties inherent in field tests to be substantially overcome. It provides in effect a multi-path transmitting medium in the laboratory, the number of paths, the time-delay differences between the paths, the path attenuations and the fading rate being adjustable at will. The fading produced can be either "dynamic," i.e. occurring continuously in a cyclic manner with fading rates ranging from about 0-1 to 10 fades/sec, or it can be "static," i.e. the fading can be stopped at any selected instant in the fading cycle. Random noise (either fading or non-fading) and interfering signals may be introduced so that a complete synthetic radio link may be set up. The fading machine has thus been referred to as an "artificial ether" or "artificial propagation medium."

The equipment may be arranged to accept an audio telephony signal or a telegraphy signal, and will then produce at the output a corresponding signal after multi-path transmission using single-sideband or double-sideband amplitude modulation, frequency or pulse modulation. Alternatively, it is possible to take an output at radio frequency for application to any receiver it is desired to test under fading conditions.

The diversity fading typical of spaced-aerial reception may be synthesized in the laboratory, the effective spacing between the aerials being varied as required; by applying these synthesized spaced-aerial signals to a diversity receiver it is possible to assess the performance of the receiver from the diversity aspect.
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(2) CHARACTERISTICS OF FREQUENCY SELECTIVE FADING

The characteristics of frequency selective fading which are discussed in the present Section relate to the transmission characteristics of the medium in terms of its amplitude/frequency and phase/frequency responses. The characteristics of idealized two- and three-path media are first described, and these idealized conditions are then compared with those on actual radio circuits.

(2.1) Two-path Medium

The simplest condition which gives rise to frequency-selective fading is interference between signals which have traversed two paths for which there is a time-delay difference $T$. The resultant signal at any frequency $f$ is the vector sum of two signals having a phase difference $\phi = -2\pi fT$. As the frequency is varied the amplitude of the resultant signal varies from a maximum through a minimum to a maximum again in a frequency interval equal to $1/T$, the reciprocal of the time-delay difference between the paths. If the time-delay difference $T$ is 1 millisecond, the maxima (or the minima) are spaced by 1 kc/s, which is typical of a long-distance short-wave circuit. For a frequency of 10 Mc/s the phase difference between the path signals is $\phi = -2\pi fT = 2\pi \times 10^4$ radians, and it is evident that small variations in $T$ (such as might be caused, for instance, by small changes in the height of the ionospheric layer at which reflection occurs) will give rise to considerable variations in the phase difference, and the received signal will pass through several maxima and minima. Fig. 2(a) drawn on a scale of frequency $f$ or time $t$, the interval between maxima (or minima) being $1/T$ for a frequency scale or $1/F$ for a time scale, where $F$ is the fading rate. Thus on a frequency scale the pattern indicates the variation of amplitude with frequency at a given instant of time, or on a time scale it indicates the variation of amplitude with time at a given frequency.

For some types of transmission (e.g. frequency-modulated signals) the phase/frequency characteristic of the medium is of great importance. Fig. 3 illustrates the relation between the amplitude/frequency and phase/frequency characteristics of a two-path medium for various values of the relative amplitude $R$ of the separate path signals. When the resultant signal amplitude passes through a minimum the phase undergoes a rapid change, and it is this phase discontinuity which is chiefly responsible for the severe distortion of frequency-modulated signals.

(2.2) Three-Path Medium

For a three-path medium the fading patterns for the resultant signals become considerably more complex than is the case with a two-path medium. Some examples are shown in Fig. 2(b), from which it can be seen that the fading pattern depends not only on the relative amplitudes of the separate path signals but also on the relative phases of the three carriers. The steady progression of similarly shaped patterns across the frequency scale, which is characteristic of two-path fading, Fig. 2(a), occurs only exceptionally under the three-path condition, Fig. 2(b).

(2.3) Fading on Actual Radio Circuits

Potter's investigation provides the most comprehensive information available on the fading characteristics of a long-distance short-wave radio channel. His investigation was carried out by means of "multi-tones," 12 audio tones spaced by 170 c/s in the range 425-2 295 c/s, being applied as modulation to double- and single-sideband short-wave senders. The radio path used for the tests was that between Deal, New Jersey, U.S.A., and New Southgate, England. By observing on an oscilloscope the relative levels of the received tones, it was possible to record the variations of the amplitude/frequency characteristic of the radio path. It should be noted that only single-sideband operation and reception is capable of indicating the r.f. characteristics of the medium; if double-sideband operation is used the received audio signal is subject to distortion which prevents the audio
Potter concludes that "from a careful comparison of synthetic two-path multi-tone characteristics with those observed throughout the year we are led to the conclusion that the selective fading on the Deal—New Southgate circuit, except for a small percentage of the time, is the result of signals travelling over more than two paths between transmitter and receiver. Synthetic patterns based upon the assumption that three paths exist between transmitter and receiver may be made to correspond rather well with the majority of observed multi-tone patterns."

Evidence of the existence of multiple-path propagation is also provided by pulse transmissions and by highly directional steerable aerial systems such as the musa (multiple unit steerable antenna) which is capable of indicating the directions of arrival of the separate path signals at the receiver. The musa data shows that the maximum group time-delay difference for signals which have traversed the transatlantic path is of the order of 3 milliseconds, the longer delays corresponding to the more steeply down-coming rays. The group time-delay differences are in general greater at the lower frequencies in the short-wave band.

The foregoing observations are concerned with a particular short-wave circuit—the transatlantic circuit which has a length of about 3000 miles. It is probable that shorter circuits would show less complex propagation, and that the two-path condition would occur as frequently as, or more frequently than, the three-path condition on the transatlantic circuit. On the other hand, longer circuits such as the England to Australia circuit may be expected to show even more complex conditions, and the synthesis of these conditions may be difficult.

(3) PRINCIPLES AND DESCRIPTION OF THE FADING MACHINE

After consideration of the fading characteristics of radio circuits and the problems to be investigated, the main features to be incorporated in the equipment were specified as follows:

(a) Three transmission paths were required, path 1 being a reference path and paths 2 and 3 of adjustable delay and attenuation.

(b) The facility was required for adjusting the group time-delay differences between paths 1, 2 and between paths 1, 3 in steps up to a total of at least 2 milliseconds.

(c) The facility was required for adjusting the phase differences between paths 1, 2 and between paths 1, 3 from 0 to 360 degrees, either manually ("static" fading) or continuously ("dynamic" fading).

(d) In the dynamic fading condition, it was desired to simulate fading rates between 0.1 and 1 fades/sec.

(e) The equipment was required to be suitable for investigating the effects of fading on double-sideband, single-sideband, frequency-, phase- or pulse-modulated signals with telegraphy, telephony or facsimile modulation.

(f) The facility for investigating diversity reception using spaced aerials was required.

(g) Outputs were required at a suitable frequency in the short-wave band so that fading signals could be applied to any receiver it may be desired to test.

(h) The facility was required for adding random noise, either fading or non-fading, so as to enable the effect of either distant or local noise on the reception of fading signals to be investigated.

The design of the fading machine described in the present paper was conditioned to a large extent by the delay networks which were readily available at the time. Audio delay networks were in fact used, the networks being identical with those intended for use in the musa receiver for delay correction and combination of the audio signals corresponding to the various transatlantic radio paths.

(3.1) System with "Static" Fading

A simplified block schematic diagram of the fading machine arranged for "static" fading is shown in Fig. 4(a).

The audio signals (100 c/s-6 kc/s) originate from a common source and feed three separate paths, path 1 being the reference path, while paths 2 and 3 are provided with adjustable time-delay networks. The delay networks are adjustable in steps of 30 microsecond up to a maximum of 2 milliseconds, approximately, and the attenuation/frequency characteristic is flat to within 0.4 db over most of the audio band. The flatness of the attenuation/frequency characteristic is of importance in tests where all frequencies in the band are to be subjected to equal and deep fading. The three audio signals are applied to three modulators M1, M2 and M3 fed with carrier at a frequency of 100 kc/s derived from the oscillator O. The modulators produce double-sideband amplitude-modulated carriers having the same shape of modulation envelope but different time-delays between the envelopes. In order to simulate the effect of small changes of path length and time-delay difference, the phase of the 100-kc/s carrier fed to the modulators is made adjustable from 0° to 360° by rotary phase shifters. It is of interest to note that the audio time-delay in the fading machine may be identified with the "group time-delay" of a radio signal transmitted via a refracting medium, and the carrier phase shift may be identified with the "phase length" of the radio path. The setting of the phase shifters determines the instant of the fading cycle under examination at a given time, and the corresponding location of the fading pattern on the frequency
scale; for instance, in the two-path case one rotation of the phase shifter corresponds to one fading cycle and a movement of the pattern along the frequency scale of \(1/T \text{ c/s} T\) being the time-delay difference between the paths. In order to set up various relative amplitudes of the delayed and non-delayed signals, attenuators are introduced in paths 2 and 3 following the modulators. The attenuators enable the depth of fading to be controlled: for instance in the two-path case 1 db difference of attenuation between the paths corresponds to a fading depth (max. to min.) of 25.5 db. The three radio signals are combined to yield a resultant signal representing transmission over three radio paths of different attenuation and time-delay characteristics.

(3.1.3) Double-Sideband Signals.
In order to demonstrate the reception of double-sideband signals with fading, the combined 100-\(106 \text{kc/s}\) double-sideband signal is applied to a linear detector to yield an audio signal.

(3.1.2) Single-Sideband Signals.
For the reception of single-sideband signals one sideband of the combined signal is selected in a 100-1-\(106 \text{kc/s}\) channel filter. The selected sideband is applied to a demodulator fed with a 100-\(106 \text{kc/s}\) carrier derived from the oscillator \(O\). This arrangement simulates the conditions usually obtaining in single-sideband reception of short-wave signals, in which a non-fading carrier of higher level than the sideband-signal is used in the demodulator.

(3.1.3) Frequency-Modulated Signals.
The effects of selective fading on frequency-modulated signals may be demonstrated by the arrangement shown in Fig. 5. Frequency modulation of an oscillator with a mean frequency of 103 \(\text{kc/s}\) is effected in the conventional manner by means of a valve reactor (Fig. 5(a)). The frequency-modulated 103-\(106 \text{kc/s}\) carrier is then translated to 3 \(\text{kc/s}\) by frequency changing with a 100-\(106 \text{kc/s}\) carrier applied to the audio input to the fading machine. The maximum frequency deviation is limited to about \(\pm 2.5 \text{kc/s}\) and the highest modulating frequency to some 3 \(\text{kc/s}\) in the present form of the fading machine, because of the limited bandwidth of the delay networks; nevertheless these limits are sufficient for the investigation of the effects of selective fading on telegraph and facsimile signals or on commercial-quality speech. The reception of the frequency-modulated signal may be carried out using the arrangement shown in Fig. 5(b) consisting of an i.f. amplifier (100-106 \(\text{kc/s}\)), a limiter and a discriminator. Alternatively, the frequency-modulated 3-\(\text{kc/s}\) sub-carrier with fading may be taken from the “single-sideband audio” or “double-sideband audio” outputs of the fading machine. The latter condition corresponds to the use of a frequency-modulated audio sub-carrier transmitted over a double-sideband amplitude-modulated radio system—an arrangement sometimes used for facsimile transmission.

(3.1.4) Pulse-Modulated Signals.
The chief form of pulse-modulated signals so far employed in investigations using the fading machine has been pulses corresponding to c.w. on/off keying. These are conveniently produced as keyed audio tone, the keying being effected by d.c. telegraph signals applied to a “static” relay (a bridge network of copper-oxide rectifiers, giving free transmission for one polarity of the d.c. signal and high attenuation for the reverse polarity). The d.c. signals may be keyed from a Wheatstone telegraph transmitter fed with perforated paper strip.

(3.1.5) Random Noise.
In order to enable the effect of random noise on fading signals to be studied, provision is made for the insertion of noise which is either “local” to the receiver (non-fading), or “distant” (subject to fading either similar to that of the wanted signal or fading which is selective to greater, or less degree than that of the signal).

“Local” noise is applied only in the reference path 1, “distant” noise is applied simultaneously in the reference path 1 and at points in the delay units of paths 2 and 3. If the noise is inserted at the input to the delay units it is subject to the same fading as the signal, if applied at intermediate points in the delay units the fading of the noise is selective in frequency but to a less degree than that of the signal.

(3.2) System with “Dynamic” Fading
It would be possible to produce continuous fading by driving the rotary phase shifters shown in Fig. 4(a) by motors at suitable speeds. A more elegant solution, shown in Fig. 4(b), consists in feeding the modulators M1, M2 and M3 from separate oscillators 01, 02 and 03. The oscillators are crystal-controlled but oscillators 02, 03 may be shifted in frequency up to a few cycles per second relative to the frequency of the reference oscillator 01 by means of variable condensers connected in parallel with the quartz crystals. A frequency difference of \(x \text{ c/s}\) corresponds to a rate of change of phase of \(2\pi x \text{ radians/sec}\), i.e. is equivalent to rotating the corresponding phase shifter at the rate of \(x \text{ rotations/sec}\); the fading rate so produced being \(x \text{ fades/sec}\). Stable fading rates from 0-1/sec to 10/sec can readily be produced.

(3.3) Arrangement for Diversity Reception
Spaced-aerial diversity reception depends in principle on the fact that the outputs of aerials separated in space are rarely equal, so that by selecting the best signal, or combining two or more signals, it is nearly always possible to secure better reception than with one aerial alone. The interference between waves of different time-delays gives rise to a field interference pattern over the surface of the earth. An example for the idealized two-path equal-signal case is shown in Fig. 6(b).

The wave interference pattern is rarely stable and its motion past an aerial gives rise to the variation of amplitude with time
exactly asynchronous fading corresponding to 180° diversity generalized in terms of the "diversity phase angle," synchronous.

Phase shifter 0°-360° for adjustment of diversity phase angle $\phi_d$

Audio delay unit

Audio input

Path 2

Path 1

Aerial 1

Aerial 2

Modulators

Attenuators

Output of aerial 1

Output of aerial 2

Time, frequency or distance

Amplitude

$T_f = \frac{T_f}{2} \cdot 2n / f = \frac{T_f}{2} \cdot 2n / \phi_d$

which is characteristic of fading. For the two-path case there is clearly an optimum spacing of the aerials which makes the fading exactly asynchronous, one aerial output being at a maximum when the other is at a minimum, and vice versa. In fact there are several optimum spacings which are odd multiples of the minimum value of the optimum spacing, and there are also other spacings (even multiples of the minimum value of the optimum spacing) at which fading is synchronous at the two aerials. The diversity of the fading can be conveniently generalized in terms of the "diversity phase angle," synchronous fading corresponding to zero (or 360°) diversity phase angle, and exactly asynchronous fading corresponding to 180° diversity phase angle.

Diversity reception may be simulated in the fading machine by the arrangement shown in Fig. 6(a). As shown, the equipment provides for continuous two-path fading and for two spaced aerials, the effective spacing of the aerials being varied at will by adjustment of the phase shifter controlling the diversity phase angle $\phi_d$.

(3.4) Production of a Radio-Frequency Signal with Fading

For receiver testing it is convenient to have available fading signals in the short-wave band. In practice, a signal on a single radio frequency (about 5 Mc/s) is usually sufficient, since short-wave receivers do not normally vary appreciably in their performance on fading signals as the signal frequency is varied. Suitable r.f. signals can readily be derived from the fading machine by applying the double-sideband i.f. output (94–106 kc/s) or the single-sideband i.f. output (100–1–106 kc/s) to a frequency changer, together with a crystal-controlled 5-Mc/s carrier. The radio receiver can then be tuned to either the upper or lower sideband signal from the frequency changer (4-9 Mc/s or 5-1 Mc/s) and the receiver selectivity will usually be sufficient to reject the 5-Mc/s carrier and the unwanted sideband 200 kc/s away from the wanted signal.

"Spaced aerial" signals for testing diversity receivers can be derived by similar methods to those described above for a single aerial signal, separate frequency changers being used for the separate aerial signals, with a common 5-Mc/s carrier applied to each frequency changer.

(4) INVESTIGATION OF THE EFFECT OF FADING ON RADIO-TELEPHONE SIGNALS

(4.1) Comparison of Double-Sideband and Single-Sideband Amplitude-Modulation Systems

One of the principal uses of the fading machine has been the comparison of the double-sideband and single-sideband systems of radio communication.

An important difference between the two systems is that when the carrier of a double-sideband signal is attenuated appreciably relative to the sidebands as a result of a selective fade, the signal presented to the detector in the radio receiver corresponds approximately to an over-modulated carrier, and the resultant a.f. output consists mainly of the second and higher even harmonics of the modulation frequency. This form of distortion does not arise in a single-sideband receiver where the sideband signal is demodulated against a carrier of high and constant level. These characteristics of double-sideband and single-sideband systems are, of course, well known but may be demonstrated in a very effective manner both aurally and visually on an oscilloscope with the aid of the fading machine. Oscillograms showing the distortion of a sinusoidal tone transmitted on a double-sideband basis through a two-path medium are shown in Fig. 7 for various values of $T_f$, the product of the path time-delay difference $T$ and the modulating frequency $f$. The vertical columns each show one half of a fading cycle; a phase difference of 0° between the carriers transmitted over the two paths corresponds to the fading maximum, and 180° corresponds to the minimum. With single-sideband operation the tone fades in a manner similar to that shown in the left-hand column of Fig. 7 for double-sideband operation and $T_f \approx 0$, i.e. variations of level occur, but there is no distortion no matter how large the time-delay difference between the paths.

The non-linear distortion of a double-sideband transmission due to selective fading is most severe when (a) the modulation depth approaches 100%, (b) the carrier is at the fading minimum and (c) the fading depth (maximum to minimum) is large. When these conditions are simultaneously satisfied the intelligibility...
of speech is seriously reduced and the quality of music is extremely unsatisfactory. The non-linear distortion produced on short-wave links when multi-path effects occur is often such as to make it impracticable to use split-band privacy, owing to the fact that the distortion components in such a system are not harmonically related to the fundamental components of the reproduced speech, and so have a marked adverse effect on quality and intelligibility. Similarly, multi-channel telegraphy using voice-frequency tones cannot be satisfactorily applied to short-wave double-sideband systems because of the inter-channel crosstalk arising from non-linear distortion. The freedom of single-sideband systems from non-linear distortion due to multi-path conditions constitutes one of the chief reasons for preferring single-sideband to double-sideband operation on long-distance radio links.

The general characteristics of selective fading on single-sideband and double-sideband transmissions may also be conveniently examined in terms of the effects of the fading on a uniform spectrum of random noise applied to the sender input. These effects are illustrated in the noise spectrograms of Fig. 8. There are one or more nulls in the audio-frequency spectrum. The number of nulls increases as the fading becomes more selective (increased path time-delay difference), and in the single-sideband case the nulls travel uniformly across the a.f. spectrum during the course of the fade. In the double-sideband case, it is interesting to note that the nulls produced by selective fading due to a two-path medium do not travel but remain fixed on the frequency scale, except at the minimum of a fade. Before the spectrograms were taken it was not appreciated that this would be so, but the effect may readily be confirmed by taking account of the vector relationships between carrier and sidebands which exist when a double-sideband signal is transmitted through a two-path medium.

The fading machine is particularly useful for the subjective examination of the effects of selective fading on speech and music. Experience has shown that the ear is more sensitive to selective fading when it is not highly selective in character (e.g. path time-delay difference of 100 microsec or less, corresponding to nulls in the fading pattern spaced 10 kc/s or more); under such condi-

![Fig. 8.—Noise spectrograms illustrating double- and single-sideband reception with one- and two-path propagation conditions.](image-url)

shading of the diagrams at a given point indicates the relative response of the medium at a given frequency and time, the variation of the response with frequency being shown vertically and the variation with time horizontally. The sharp cut-off of the noise spectrum in the single-sideband case is due to the sideband selecting filter which cuts off at about 6 kc/s.

With general-level fading (no path time-delay difference) all noise components fade simultaneously; with selective fading the ear readily detects a gradually changing and tilting audio response, but if the fading is highly selective (e.g. path time-delay difference of 1 millisecond or more, corresponding to nulls in the fading pattern spaced 1 kc/s or less) the changes of audio response are less readily detected and the changes of average level of the audio signal are not so marked. These effects are best illustrated with single-sideband reception since they are not then masked by non-linear distortion.
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(4.2) Frequency Modulation

When a frequency-modulated signal is subjected to selective fading due to a two-path medium, the instantaneous frequencies of the received signals due to the two paths will usually not be identical at a given time, as a result of the path time-delay difference. Fig. 9(a) shows the instantaneous frequencies of the undelayed and delayed signals for a two-path medium (path time-delay difference $T$) and for square, triangular, and sinusoidal modulation. In the case of square-wave modulation the instantaneous frequencies are different only during the interval $T$, for triangular modulation there is a frequency difference $\Delta f$ which is constant in magnitude over the greater part of the cycle but which alters in sign, and for sinusoidal modulation the instantaneous frequency difference itself varies sinusoidally with time. Frequency modulation of one path signal by the other will take place at the limiter in the frequency-modulation receiver, and, as may be seen from Fig. 9(b), the frequency-deviation due to the inter-modulation of the signals is greatest when the two signal vectors are instantaneously in phase opposition, and is least when they are instantaneously in the same phase. Thus when the amplitudes of the two signals are nearly equal and the signals are in phase opposition, the instantaneous frequency-deviation of the resultant increases suddenly to a relatively high value, and the distortion of the signal envelope after detection in Fig. 10 for the case of triangular and sinusoidal modulation envelopes.

The time position of the spikes is not fixed in relation to the modulation envelope but varies during a fading cycle. Because of the "spiky" nature of the resultant audio signal the distortion involves high-order components and is particularly unpleasant to the ear.\(^7\) The effect of the distortion on speech or music is to produce crackling or harsh grating sounds which are generally more severe at high modulation levels (large frequency deviations). The distortion is generally less severe at low modulation levels and at low frequencies. When the individual path signals are nearly equal in amplitude, the distortion is apparent for path time-delay differences as small as 100 microseconds, but persists for only a small fraction of the fading cycle. As the path time-delay difference is increased, the fraction of the fading cycle during which there is severe distortion also increases, until with 1-millisecond or more path time-delay difference the signal is subject to severe distortion nearly all the time. In general the non-linear distortion due to multi-path effects is much more severe with frequency modulation than with double-sideband amplitude modulation, and frequency modulation has therefore found little application to the transmission of telephony signals over long-distance short-wave radio links.

### Fig. 9

- **(a)** Waveform of delayed and undelayed signals.
  - Undelayed signal
  - Delayed signal
- **(b)** Vector diagram of delayed and undelayed signals.

Instantaneous frequency of resultant signal is changed by $\frac{1}{\Delta f}$, which is a maximum when $0 \cdot 180^\circ$.

\[
\Delta f = \frac{1}{2\pi} \frac{R}{1-R} \frac{d\Omega}{dt} \approx \frac{R}{8f_{\text{max}}}
\]

### Fig. 10

- **(a)** Triangular modulation.
- **(b)** Sinusoidal modulation.

Carrier deviation $= \pm 350$ c/s.
Modulating frequency $= 25$ c/s.
Time-delay difference $= 1.8$ ms.
Fading depth $= 20$ db.
Two-path condition.

![Distortion of frequency-modulated signal due to selective fading](image)

**Fig. 10.**—Distortion of frequency-modulated signal due to selective fading.

(5) INVESTIGATION OF THE EFFECT OF FADING ON RADIO-TELEGRAPH SIGNALS

(5.1) "On/off" Keying (C.W. Signals)

A keyed c.w. signal consisting of a train of "dots" comprises a carrier and a series of sideband components spaced by frequency intervals equal to the keying frequency. Under conditions of general-level fading the carrier and sideband components fade together and the signal therefore fades without change of shape. On the other hand, when the fading is selective in character, the signal suffers a change of shape as well as of amplitude; the effect of a fade can be analysed by determining how the relative amplitudes and phases of the various signal components are modified by the amplitude/frequency and phase/frequency characteristics of the propagation medium (see, for example, Fig. 3 for a two-path medium). However, the envelope of the resultant signals at the fading maximum or at the fading minimum may be calculated by addition or subtraction of the envelopes of the delayed and undelayed signals, as illustrated in Fig. 11 for the case of an ideal square-envelope signal.

It will be seen that the signal duration is lengthened by an amount $T$, and at the fading minima almost complete cancellation may occur during the period of overlap of the delayed and undelayed signals, so giving rise to the familiar "dumb-bell" type of distortion.\(^6\) In fact, of course, both signals in a two-path medium are delayed, but it is convenient to speak of the signal which suffers the greater delay as the "delayed signal" and to call the signal which suffers less delay the "undelayed signal." Thus the general effect of selective fading on c.w. signals is to cause lengthening of the signals, while at the fading minima double marking may occur. Since the amount by which the signal is lengthened depends only on the path time-delay differ-
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Signal from path 1

Signal from path 2

Resultant signal at fading minimum

Fig. 11.—Reconstruction of ideal telegraph signal at fading minimum.

\( T \) - Time-delay difference between paths.
\( d \) - Fading depth.
Two-path condition.

ence, the percentage distortion is therefore greater the shorter
the duration of the elementary signal, and the use of low sending
speeds to avoid excessive distortion under multi-path conditions
is indicated.

For perfectly square envelope signals and deep fading, the
elementary signal may be lengthened by a time \( T \), equal to the

\( (i) \) Single path (no fading)  Signal/noise ratio 10 db
\( (ii) \) Two-path \((T = 30 \mu s, d = 20\%)\) (with fading)  Signal/noise ratio 16 db at maxima
\( (iii) \) Two-path \((T = 30 \mu s, d = 30\%)\) (with fading)  Signal/noise ratio 36 db at maxima
\( (iv) \) Two-path \((T = 30 \mu s, d = 40\%)\) (with fading)  Signal/noise ratio 46 db at maxima
\( (v) \) Two-path \((T = 30 \mu s, d = 50\%)\) (with fading)  Signal/noise ratio 46 db at maxima
\( (vi) \) Two-path \((T = 30 \mu s, d = 60\%)\) (with fading)  Signal/noise ratio 20 db at maxima
\( (vii) \) Two-path \((T = 30 \mu s, d = 70\%)\) (with fading)  Signal/noise ratio 20 db at maxima
\( (viii) \) Two-path \((T = 30 \mu s, d = 80\%)\) (with fading)  Signal/noise ratio 20 db at maxima
\( (ix) \) Two-path \((T = 30 \mu s, d = 90\%)\) (with fading)  Signal/noise ratio 20 db at maxima

Fig. 12.—Undulator records of c.w. telegraph signals.
(a) Single receiver.
(b) 2-aerial diversity.

Fig. 13.—Pulse distortion due to selective fading.

Upper trace: d.c. output of bridge.
Lower trace: tone input to bridge.
Fading depth — 30 db.
Fading rate — 1 in 2 seconds.
\( T \) - Time-delay difference between the two paths.
path time-delay difference, and the percentage distortion is given by

$$\text{Distortion} = 7S \times 100\%$$

where $S$ = speed in bauds. Thus for a path time-delay difference of 2 millisees and a speed of 50 bauds the theoretical distortion is 10%, while at 200 bauds the theoretical distortion rises to 40%.

These general conclusions are confirmed by a study of Figs. 12 and 13 which show the results of fading-machine tests on a communication-type receiver.

Fig. 12(a) shows undulator tape records taken on reversal at a sending speed corresponding to 150 words/min. Record (i) shows that in the absence of fading a signal/r.m.s.-noise ratio of 10 db in a 400 c/s bandwidth is sufficient to give faultless recording; records (ii) to (iv) show that with a general level fade of 30 db (maximum to minimum) the signal/noise ratio at the fading maxima must be increased to at least 40 db to avoid errors at the fading minima. Record (v) shows that if the fading is made selective the signal/noise ratio at the maxima is high. In other words the effects of general-level fading may be overcome by increasing the transmitter power, but the same is not true, no matter how great the increase of power, when the fading is highly selective.

Fig. 13 shows oscillograms of the tone output from the receiver and of the d.c. output from the telegraph bridge, for signal speeds of 50 w.p.m. and 150 w.p.m. The rounded envelope of the tone signals at the higher sending speed results from the use of a narrow band-pass filter (400-c/s bandwidth) at the output of the receiver, and the overshoot on the leading edge of each pulse at the lower sending speed is due to the receiver automatic gain-control action. Comparison of record (a) with (d) and of (b) with (e) shows the marked increase of distortion with sending speed, for a given time-delay difference between paths. Record (a) also shows an example of "dumb-bell" distortion at the fading minimum.

(5.2) Two-tone V.F. Telegraph

From the tests with c.w. signals, it is clear that multi-path conditions set an upper limit to the permissible sending speed, and it is apparent that under such conditions a given frequency band may be utilized to greater advantage by a number of relatively low-speed transmissions (for example, teleprinter signals at 50 bauds) than by a single very-high-speed transmission. The effective transmission of teleprinter signals necessitates a low level of telegraph signal distortion, and considerable attention has been paid to various methods for achieving this object. One practical solution is the transmission, over a single-sideband radio-link, of a group of voice-frequency (v.f.) tones, the tones being spaced at intervals of 120 c/s and each pair providing a telegraph channel; one tone of each pair is transmitted in the marking condition and the other in the spacing condition of the telegraph signal. The chief advantage of two-tone operation as compared with single-tone is the improved performance obtainable under fading and high noise-level conditions.

In the standard v.f. receiving equipment, the mark and space tones are selected in filters having an effective bandwidth of approximately 100 c/s, and are then amplified and rectified. The rectified signals operate a push-pull d.c. amplifier, in the anode circuit of which is the receive telegraph relay. This equipment accommodates a wide range of input level variation by means of limiting in the d.c. amplifier, and the preceding audio-tone amplifier. It is important, however, that level differences between mark and space tones should be kept to a minimum since the instant of operation of the receive relay is determined by the instant at which the mark and space tones pass through equality of level as one tone builds up and the other decays. Level differences due to selective fading are minimized by close spacing of the tones, but cannot be completely avoided.

Tests with non-fading signals have shown that a signal/noise ratio of 13 db (measured in a bandwidth of 100 c/s) is required if the errors are not to exceed an average of 1 per 1 000 characters.

(5.2.1) Effect of Selective Fading on Standard Two-Tone V.F. System (120 c/s Spacing).

An investigation of the effects of selective fading on two-tone v.f. telegraph signals was made, using the fading machine arranged as shown in Fig. 14. The keying signals in this case were derived from a telegraph distortion-measuring set (t.d.m.s.) to which the d.c. signals from the receive relay were returned; the distortion could then be read directly on the t.d.m.s. as the difference in duration of a received signal relative to the corresponding transmitted signals, and expressed as a percentage of the duration of an elementary signal. Alternatively, in certain tests, the received signals were applied to a telegraph distortion monitor which counted automatically the number of times in a given period the distortion exceeded an assigned value; by repeating the measurement for several values of the distortion, it is possible to obtain a probability distribution of the distortion.

Using the "static" fading condition (Section 3.1) and measuring the percentage distortion for various settings of the phase shifter, records of the type shown in Fig. 15 were constructed showing

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**Fig. 14.** Arrangement of equipment for 2-tone v.f. telegraph tests. The keying signals in this case were derived from a telegraph distortion-measuring set (t.d.m.s.) to which the d.c. signals from the receive relay were returned; the distortion could then be read directly on the t.d.m.s. as the difference in duration of a received signal relative to the corresponding transmitted signals, and expressed as a percentage of the duration of an elementary signal. Alternatively, in certain tests, the received signals were applied to a telegraph distortion monitor which counted automatically the number of times in a given period the distortion exceeded an assigned value; by repeating the measurement for several values of the distortion, it is possible to obtain a probability distribution of the distortion.

Using the "static" fading condition (Section 3.1) and measuring the percentage distortion for various settings of the phase shifter, records of the type shown in Fig. 15 were constructed showing

**Fig. 15.** Variation of telegraph signal distortion during a fading cycle. Sending speed = 50 bauds. Path time-delay difference = 1 ms. Two-path condition.
how the percentage distortion varies during a fading cycle. Similar measurements were made to determine the effect of path time-delay difference and signalling speed, and the results are expressed in Figs. 16–17.

The oscillograms of Fig. 18 show that, in addition to the mutilation of the signal envelope due to selective fading, a considerable level disparity may still exist between the mark and space tones at the minimum of a highly-selective fade (path time-delay difference \( \approx 2 \text{ milliseconds} \)), even though the tone spacing is small (120 c/s). The relatively slow build-up and decay of the signal envelope accentuates the distortion due to any level disparity between the mark and space tones, an effect which may be mitigated (at the expense of increased bandwidth) by using substantially square envelope signals as against the rounded envelope signals of the standard two-tone v.f. system. Such a system corresponds closely to the frequency-shift system discussed in Section (5.3).

(5.2.2) Summary of Results of Tests on Standard Two-Tone V.F. System.

Summarizing the results, it is concluded that:

(a) The increase of distortion due to fading, above that inherent in the equipment, is approximately proportional to signalling speed for the range of speeds which may be used in practice (40–80 bauds).

(b) The distortion is independent of the fading rate within wide limits.

(c) The fading depth and degree of selectiveness must be considered together, and the way in which the distortion varies with these factors cannot be simply expressed. Very broadly it can be said, however, that when the fading has a marked frequency-selective character considerable distortion will result if the fading depth (maximum to minimum) is in excess of 10 db.

This last result means that on long-distance, short-wave radio links the propagation conditions will frequently be such as to cause considerable distortion of two-tone (120-c/s spacing) v.f. telegraph signals. This fact has already been recognized in practice, and it is customary on short-wave radio-telegraph circuits to use frequency diversity or spaced-aerial diversity methods of transmission and reception to minimize the distortion; diversity reception of telegraph signals is discussed in Section 6.2.

(5.3) Frequency-Shift Telegraphy

Another development in recent years, which has proceeded side by side with the advances in multi-channel v.f. telegraphy, is the frequency-shift system of telegraphy,\(^{12}\) mainly used at present for single-channel operation as an alternative to on/off keying. This is in effect a frequency-modulation system using square-wave modulation, in which the carrier frequency is deviated in one direction to indicate a mark and in the other direction to indicate a space. Experience on actual radio
The investigation of the effects of frequency-selective fading has shown that this system of communication yields a high standard of performance even at relatively high keying speeds and under adverse propagation conditions.

The fading machine has been employed to obtain information on the effect of fading on frequency-shift signals using the arrangement shown in Fig. 5 and discussed in Section 3.1.3. The receiver used incorporated a limiter followed by a linear discriminator. The output signals from the discriminator were viewed on an oscilloscope both before filtering and after filtering in a low-pass filter with a cut-off at 450 c/s.

It was observed that when the fading was selective in character the beginning of each signal element was subject to an oscillatory disturbance. This arises from the fact that, in a two-path medium having a time-delay difference between paths, there will be an interval of time during which the mark signal due to one path will be present at the limiter simultaneously with the space signal due to the other path, and the two signals will beat together during the period of overlap.

This action is illustrated in Fig. 19 for square-envelope modulation; in this case the period of overlap is equal to the path time-delay difference and the frequency of the beat between the signals during the overlap is equal to the frequency shift. Since the time-delay difference is the same in all cases, the period of signal overlap extends over a greater proportion of the signal as the sending speed is raised.

Fig. 20(a) illustrates the effect for substantially square signals at different sending speeds. Since the time-delay difference is the same in all cases, the period of signal overlap extends over a greater proportion of the signal as the sending speed is raised.

FIG. 19. Reconstruction of ideal frequency-shift signal subjected to selective fading.

T Time-delay difference between paths for two-path condition.

Mark frequency \( f_1 \)
Space frequency \( f_s \)

Signal at limiter from path 1

Mark frequency \( f_1 \)
Space frequency \( f_s \)

Signal at limiter from path 2

Beat frequency \( f_1 - f_s \)

Resultant d.c. output from discriminator

Time

Fig. 20.—Signal envelope of frequency-shift signals subjected to selective fading, showing the effect of variation of sending speed.

(a) Before filtering.

(b) After filtering (450-c/s low-pass filter).

Path time-delay difference 1.8 ms.

Fading depth 20 db.

Carrier deviation 350 c/s.

(5.3.1) Effect of Selective Fading on Frequency-Shift Signals.

It has already been noted that the effect of two-path propagation on a frequency-shift signal is to give rise to a beat-frequency transient (as shown in Fig. 20) due to the simultaneous existence of two signals of different frequencies at the limiter input. It may be shown that the mean frequency obtained from a limiter, when two similar signals of different frequencies and amplitudes are applied to the input of the limiter, is substantially equal to the frequency of the stronger signal, even for signal amplitudes close to equality. Thus if a linear discriminator is used giving a d.c. output proportional to the mean frequency of the applied signal, the received telegraph signal will be substantially undistorted. The linear discriminator should follow the relatively slow wanted modulation of the frequency-shift signal, but should not follow the unwanted transient at the beat frequency. This is generally practicable if the frequency-shift is appreciably greater than the highest significant modulating frequency of the telegraph signal.

So far the attenuation over the two paths has been assumed to be stable, but in practice the two signals vary in relative level. If the path-1 signal gradually increases in level from below the path-2 signal, through equality to a higher level, the time-delay...
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of the resultant signal at the discriminator output changes from
the delay appropriate to path 2 to that appropriate to path 1.
With an effective limiter the change of time-delay occurs for a
very small predominance of one signal over the other, so that
possibly only one signal element is distorted during the change
of level. This may be compared with c.w. on/off keying
(Section 5.1) and two-tone working (Section 5.2) where all
the signal elements may be subject to distortion while the multi-path
condition with deep fading persists.

It is considered that the foregoing accounts to a large extent
for the effectiveness of the frequency-shift system under severe
selective fading conditions.

(5.3.2) Tests with Frequency-Shift Signals.

Fading machine tests, using a receiver with a limiter followed
by a linear discriminator, confirm the comparative immunity
from multi-path distortion of telegraph signals transmitted by
the frequency-shift method.

Fig. 21 shows the effect of one cycle of deep selective fading;
comparison of the sent and received d.c. signals (records (a)
and (b)) shows that the signal distortion is always small,

![Fig. 21.—Effect of selective fading on frequency-shift telegraph signals.](image)

Records (c) and (d) show respectively the signal at the input to
the limiter and the waveform of the unfiltered signal at the output
of the discriminator.

The effect of random noise and fading on frequency-shift signals
was investigated by setting up a complete teleprinter channel
operating through the two-path medium of the fading machine.
The frequency-modulated oscillator shown in Fig. 5 was modu-
lated by signals from a teleprinter auto-transmitter which con-
tinuously repeated a standard character sequence commonly
used in teleprinter testing. The received d.c. signals were used
to operate a teleprinter. With a non-fading signal and random
noise injected locally to the receiver, the minimum signal/noise
ratio for faultless printing was + 6 db, measured in the 2-3-kc/s
i.f. bandwidth of the frequency-modulation receiver. A reduc-
tion of the signal/noise ratio to + 5 db produced errors averaging
3 per 1 000 characters, while a further reduction to + 4 db
produced a severe deterioration and the printing became prac-
tically unintelligible. Results obtained with combined fading
and noise were consistent with the foregoing, the minimum
signal/noise ratio for satisfactory printing being + 6 db at
the minimum of a fade. Thus with a 30-db fade and a path time-
delay difference of 2 milliseconds a signal/noise ratio of + 36 db at
the fading maximum was necessary for faultless printing.

(5.3.3) Simulation of Frequency-Shift Signals by Keyed Two-Tone
Signals.

It is apparent that a frequency-shift signal with square-wave
modulation may be closely simulated by alternate on/off
keying of two oscillators, the frequencies of which differ by the
required frequency shift. In a practical sending system such an
arrangement might be preferred to a true frequency-shift system
of signalling because of its simplicity and the good frequency
stability obtainable. An investigation was therefore undertaken
to determine the extent to which the two methods of signalling
are in fact equivalent. It was found that when the envelope of
the keyed tones was sufficiently square the performance on
printing tests was closely comparable to that obtained with true
frequency-shift signals; similarly a comparison of transmitted
and received signal envelopes gave results almost identical with
those shown in Fig. 21 for frequency-shift signals, under similar
propagation conditions.

![Fig. 21.—Effect of selective fading on frequency-shift telegraph signals.](image)

In the Hell-printer system each character is transmitted as a
train of impulses, the sequence and length of the constituent
mark and space signals of any character being determined by a
scanning process. For automatic working the printing speed is
50 w.p.m. and the telegraph speed is 245 bauds. Because the
Hell system is essentially a facsimile system, the performance is
most conveniently judged by inspection of the tape records.

Modulated continuous wave (m.c.w.) transmissions have been
widely used for Hell-printer services, the carrier being modulated
to a depth of 80% by a 900-c/s tone, and the modulated carrier
keyed by impulses from the Hell transmitter. The signals are
received in a communication-type radio receiver, the tone output
being converted into d.c. by a valve trigger circuit for operation
of the Hell printer.

(5.4.1) Effect of Selective Fading on Hell-Printer Signals Transmitted
by M.C.W.

The effect of fading on Hell-printer signals transmitted by
m.c.w. is shown in Fig. 22.

Record (a) shows the effect of non-selective fading having a
range of 30 db, the noise being of low level. It is evident that
the receiver automatic gain-control and the trigger circuit are
effective in preventing the fading from affecting the quality of
the received signal. Records (b) to (d) show the effect of fading of similar range to (a) but of increasing selectivity. The distortion of the characters in record (d) for two paths with 2-millisecond time-delay difference is marked, particularly at the fading minima which occur at about every sixth or seventh character. The effect of a random noise background is shown in record (e) for similar conditions to record (d) (30-db fading depth, 2-millisecond path time-delay difference), but with 30 db of limiting to minimize the distortion of the characters due to fading. The signal/noise ratio at the fading maxima was 40 db and at the minima it was 10 db, the i.f. bandwidth being 3-6 kc/s. The random noise causes false marks during the inter-word spaces and when the signal/noise ratio is inadequate, i.e. at the fading minima.

(5.4.2) Effect of Selective Fading on Hell-Printer Signals Transmitted by Frequency-Shift.

In view of the good results obtained with frequency-shift for the transmission of teleprinter signals (see Section 5.3.2), tests were also made on a Hell-printer system employing the frequency-shift method of signalling.

A marked advantage of the frequency-shift system was found to be its ability to provide nearly faultless printing under conditions of highly selective fading. Record (b) in Fig. 23 illustrates printing obtained when the signal/noise ratio is large, the fading depth 30 db and the path time-delay difference 2 milliseconds; this record may be compared with record (d) in Fig. 22 for an m.c.w. signal under the same fading conditions.

The effect of random noise on a frequency-shift Hell-printer system is to cause non-operation rather than false operation of the printer electromagnet; this effect is illustrated in records (c) to (e). Partly because incomplete characters appear to be easier to read than characters masked by noise, the frequency-shift system showed an improvement of up to 15 db in the minimum signal/noise ratio for satisfactory printing as compared with the m.c.w. system when a background of random noise was added under highly-selective fading conditions.

This point is illustrated by comparing record (e) in Fig. 22 (m.c.w., 30-db fading depth, 2-millisecond time-delay difference between paths, 40 db signal/noise ratio at fading maxima) with record (d) in Fig. 23 (frequency-shift, 25-db signal/noise ratio at fading maxima, other conditions as for m.c.w.). If the systems are compared on a basis of equal peak transmitted powers there is a further improvement of 6 db in favour of frequency-shift as compared with m.c.w.

With a non-fading signal the improvement in the minimum signal/noise ratio for satisfactory printing is from about 7 db in a 3-6-kc/s bandwidth for the m.c.w. system to about 2 db in a 2-3-kc/s bandwidth for frequency-shift.

(6) INVESTIGATION OF THE EFFECT OF FADING ON DIVERSITY RECEPTION

(6.1) Radio-Telephone Signals

The fading machine has been used, in the manner described in Section 3.3, to make subjective observations on various
methods for utilizing the speech or music outputs of radio-telephone receivers working in spaced-aerial diversity. The circuit arrangement of the fading machine for these tests is shown in Fig. 6.

(6.1.1) Double-Sideband Reception of Telephone Signals.

Direct combination of the audio speech or music signals is sometimes employed. In general, the predominant audio signal will be the least distorted signal and it will "mask" to some extent the lower-level distorted signals so that a useful improvement can be obtained. If two strong i.f. signals are present in separate receivers, it is probable that they will have approximately the same envelope delay, so that after detection the two audio signals will tend to add in phase, whereas the noise contributions will tend to add in random phase and a signal/noise improvement of a few decibels may be obtained. Another simple arrangement, which has been used for double-sideband signals, consists in applying the i.f. signals to separate diodes sharing a common load resistor. This arrangement ensures that the audio output is determined mainly by the envelope of the i.f. signal of predominant amplitude. Tests have shown this method to yield some improvement as compared with direct combination in that the rejection of the lower-level distorted signals is improved, but unfortunately conditions may arise (infrequently) where the resultant audio output is inferior to that which may be obtained from the best receiver, so that the method is by no means a complete solution.

(6.1.2) Single-Sideband Reception of Telephone Signals.

A difficulty which arises in the single-sideband reception of telephone signals on a diversity basis is that the phases of the audio components at the separate receiver outputs tend to be of random relationship, particularly when a common local carrier is applied to the demodulators. Even if "reconditioned" carrier is used, its phase is subject to variations imposed by fading and by frequency shifts of the pilot carrier in the narrow-band carrier filter, and these phase variations are translated to the audio signals so that it is by no means certain that the audio signals will add in phase. Thus the simple method of direct combination is not as effective as in the double-sideband system.

One method, which has been applied experimentally, uses an electronic switching device to compare the levels of the audio signals and to select (nearly instantaneously) the audio signal of highest level. Tests using the fading machine have shown, however, that it is not easy to prevent the switching from being apparent when the fading is not very selective in character, since the ear readily detects a change from an audio response with a tilt in one direction to one with a tilt in the opposite direction.

Observations have shown that the tilting of the a.f. response is much less noticeable when the fading is highly selective (path time-delay difference of 1 millisec or more). These observations suggest that the diversity reception of telephone signals may be improved by subjecting the audio outputs of the receivers to different values of time-delay and then combining them.

Tests in the laboratory, using two-aerial diversity outputs from the fading machine, showed promising results. For the test, one output was passed through a 3-millisec a.f. time-delay network and then combined with the undelayed output. When the fading was not highly selective but deep, the tilting and changing character of the audio response with a single receiver was quite apparent; with two receivers in diversity and using audio delay combination the fading was scarcely detectable.

(6.2) Radio-Telegraph Signals

(6.2.1) On/Off Keying (C.W.).

D.C. combination of the output signals of telegraph receivers working in diversity is the most satisfactory method and is almost invariably employed. The performance of some spaced-aerial diversity c.w. telegraph receivers has been investigated with the aid of the fading machine. Two-aerial diversity working was used, and it is convenient to denote the amount of asynchronous between the fading signals at the outputs of two spaced aerials by the diversity phase angle.

The results obtained using a typical diversity receiver are conveniently shown by means of undulator tape records as in Fig. 12. The results shown are for the optimum diversity phase angle of $180^\circ$. This is, of course, the ideal case for two-aerial diversity reception, since it ensures that at any instant a signal is present in one of the receivers no matter how deep the fading may be. Nevertheless, it has been established that the benefits of diversity reception hold without appreciable modification for a wide range of diversity angles (from about $45^\circ$ to $315^\circ$). In practice three-aerial diversity reception is used rather than the two-aerial diversity employed in the tests, and this ensures a high degree of probability that the diversity phase angle, for at least one pair of aerials, will lie in the range quoted. For the tests shown in Fig. 12, a two-path propagation medium was used, the fading depth being 30 db. The minimum signal/noise ratio for satisfactory recording with a single receiver and a non-fading signal was 10 db for a bandwidth of 400 c/s [record (i), Fig. 12(a)].

Records (vi) and (viii) of Fig. 12(b) show undulator records, with two receivers working in diversity, for short (30 microsec) and long (2 millisec) path time-delay differences respectively, the signal/noise ratio being 10 db at the fading maxima and 20 db at the minima. The failures which occurred at the fading minima in records (vi) and (viii) are not present in records (vii) and (ix), which show that an increase of signal input of 10 db (20 db signal/noise ratio at the maxima) was sufficient to yield satisfactory recording. These records illustrate the advantages obtainable with diversity reception. In particular, taking the case of a 2-millisec path time-delay difference, the improvement of record (ix) over record (v) is marked and is, moreover, an improvement which cannot be obtained merely by increasing the transmitter power.
(6.2.2) Two-Tone V.F. Telegraphy.

The improvement to be obtained by the use of two-aerial diversity reception has also been investigated for the case of two-tone v.f. telegraph signals (as described in Section 5.2). A two-path propagation medium, having a path time-delay difference of 1 millisecond and a fading depth of 30 db, was chosen for the tests. The variation of percentage distortion during a complete fading cycle, for various values of diversity phase angle between 0° and 360°, was measured using a telegraph distortion-measuring set. From the results obtained, a series of curves of the type shown in Fig. 15 was drawn from which it was possible to calculate, for each value of diversity phase angle, the proportion of fading cycle during which a given value of distortion was exceeded. From this information, and by assuming that all values of diversity phase angle were equally probable, (a condition which is likely to be approached in a system required to work over a wide frequency range) the lower curve of Fig. 25 was derived.

![Fig. 25. - Telegraph signal distortion for single-aerial and two-aerial diversity reception.](image)

For the purpose of comparison, the corresponding curve for the single-receiver case is also shown. The results show, for instance, that the use of two-aerial diversity reduces the percentage of time for which the distortion exceeds 20%, from 37% for one-aerial to 8% for two-aerial diversity. These distortion figures may appear to be high, but it should be noted that the fading conditions simulated are representative of severe rather than average propagation conditions. Moreover, a further substantial improvement could be expected from the use of a third aerial.

(7) CONCLUSIONS

Experience with the fading machine during the past two years has shown it to be an invaluable aid to the designer of short-wave radio telephone and telegraph sending and receiving systems. In many cases it has enabled systems to be compared in the laboratory in a matter of days when field trials under actual propagation conditions would have necessitated several weeks of work and considerable expense. It has enabled the manner in which different systems react to noise and fading to be analysed and studied in detail, so assisting in effecting improvements in design and performance. The facility for precisely controlling and repeating the conditions of test has been found to be of great value.

The use of the equipment requires some knowledge of the fading characteristics of actual radio links, in particular the number of paths involved, the relative path attenuations and delays, and the manner in which these quantities vary with time. Information of this kind is comparatively scanty at present and more is desirable if the most effective use of the fading machine is to be made.

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