RECOMMENDATION ITU-R S.446-4*

Carrier energy dispersal for systems employing angle modulation by analogue signals or digital modulation in the fixed-satellite service

(1966-1974-1978-1992-1993)

The ITU Radiocommunication Assembly,

considering

a)   that use of carrier energy dispersal techniques in systems in the fixed-satellite service can result in a substantial reduction of interference to stations of a terrestrial service operating in the same frequency bands;

b)   that in many cases the use of such techniques can result in a moderate to substantial reduction in the level of interference between systems in the fixed-satellite service operating in the same frequency bands, although in other cases the use of such techniques may not reduce the level of interference between such systems;

c)   that such techniques are being regularly and successfully employed in systems in the fixed-satellite service without noticeable deterioration of the quality of operation;

d)   that Recommendation No. 103, relating to carrier energy dispersal in systems in the fixed-satellite service, was adopted by the World Administrative Radio Conference for Space Telecommunications (Geneva, 1979);

e)   that performance evaluation of various techniques of FM-TV signal dispersion is given in Annex 1 to Recommendation ITU-R S.671,

recommends

1   that systems in the fixed-satellite service should use carrier energy dispersal techniques, as far as is practicable and in a manner consistent with satisfactory operation of the systems, with a view to spreading energy such that the interference to stations of a terrestrial service operating in the same frequency bands is maintained within specified tolerable limits at all times;

2   that the capability for carrier energy dispersal up to the maximum degree practicable should be included in the design of satellite systems to be available for implementation when necessary to maintain a reduced level of interference between systems in the fixed-satellite service operating in the same frequency bands;

3   that the following Note should be regarded as part of this Recommendation:

NOTE 1 – Annex 1 describes various dispersion techniques for use with FM analogue and PSK digital signals which can be recommended for practical utilization.

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*   Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

ANNEX 1

Energy dispersal in the fixed-satellite service

1   Introduction

It is clear from studies of frequency sharing between the fixed-satellite service and terrestrial radio-relay systems and between different fixed-satellite networks that, to ensure that mutual interference between the systems is kept to a tolerable level, it will be essential in most cases to use energy dispersal techniques to reduce the spectral energy density of the transmissions of the fixed-satellite service during periods of light loading. The reduction of the maximum energy density will also facilitate:

–   efficient use of the geostationary-satellite orbit by minimizing the orbital separation needed between satellites using the same frequency band; and

–   multiple-carrier operation of broadband transponders.

The amount of energy dispersal required obviously depends on the characteristics of the systems in each particular case. It is clear, however, that it is desirable that the maximum energy density under light loading conditions should be kept as close as possible to the value corresponding to the conditions of busy hour loading.

In this Annex, the results of some theoretical and experimental studies of energy dispersal techniques, separately applicable to analogue frequency-modulation and to digital radiocommuni-cation-satellite systems, are reported.

It is concluded that substantial energy dispersal can be obtained in most circumstances. However, there are some possible limitations on the efficiency of the dispersal and these are mentioned in the Annex.

2   Energy dispersal for analogue multi-channel telephony FM systems

In studying ways of achieving high degrees of carrier energy dispersal, it is useful to know what is the dispersing effect of the fully-loaded baseband signal, in order to have some reference value with which to compare what can be obtained artificially. It is legitimate, for the general class of wide-deviation frequency-modulation systems under consideration, i.e. those in which the multi-channel r.m.s. deviation (δF) exceeds the highest baseband frequency, and greatly exceeds the lowest baseband frequency, to assume that the mean power spectrum under the conventional busy-hour loading conditions is of Gaussian form. Hence, the dispersing effect obtained under these conditions is:

$$10 \log \left(\frac{\text{maximum energy per 4 kHz}}{\text{total energy}} \right) = 10 \log \frac{0.004}{\sqrt{2\pi \, \delta F}} = - \, (28 + 10 \log \delta F) \qquad \text{dB}$$

(δF is expressed in MHz)

The dispersing effect when δF is less than the highest baseband frequency can be calculated using the information contained in Annex 1 of Recommendation ITU-R S.675.

There are a number of methods of maintaining a high degree of carrier energy dispersal in telephony systems, where the obtained dispersal is a function of the complexity of the means of dispersal and the increase in occupied radio-frequency bandwidth resulting from distortion. The methods fall into one or other of two general cases; one which adds a dispersal waveform not necessarily of constant magnitude to the input signal and the second which, in addition, effectively controls the deviation sensitivity of the frequency modulator. Various arrangements of these two methods are illustrated in Fig. 1.

## 2.1   Dispersal by added waveforms

2.1.1   Method 1a)

The simplest way of bringing about some degree of carrier energy dispersal is to add to the baseband signal, a suitable low-frequency dispersing waveform of fixed magnitude, as in Method 1a) of Fig. 1. Of a variety of dispersal waveforms that have been proposed, the following are examined in this Annex:

–   a sinusoidal signal (Curve A of Fig. 2),

–   a sinusoidal signal plus 30% third harmonic added in suitable phase (Curve B of Fig. 2),

–   a band of low-frequency noise (Curve C of Fig. 2),

–   a low-frequency triangular waveform (Curve D of Fig. 2).

FIGURE 1

Simplified block diagram
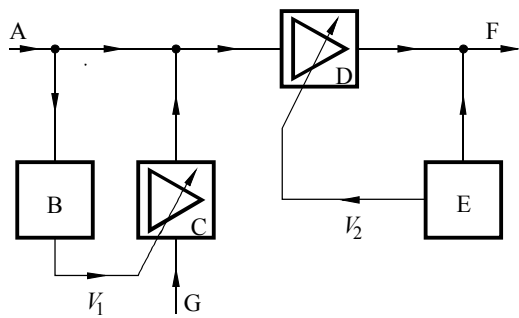
A: baseband signal input
B: r.m.s. detector
C: amplifier 1
D: amplifier 2
E: r.m.s. detector
F: output to frequency-modulator
G: dispersal waveform
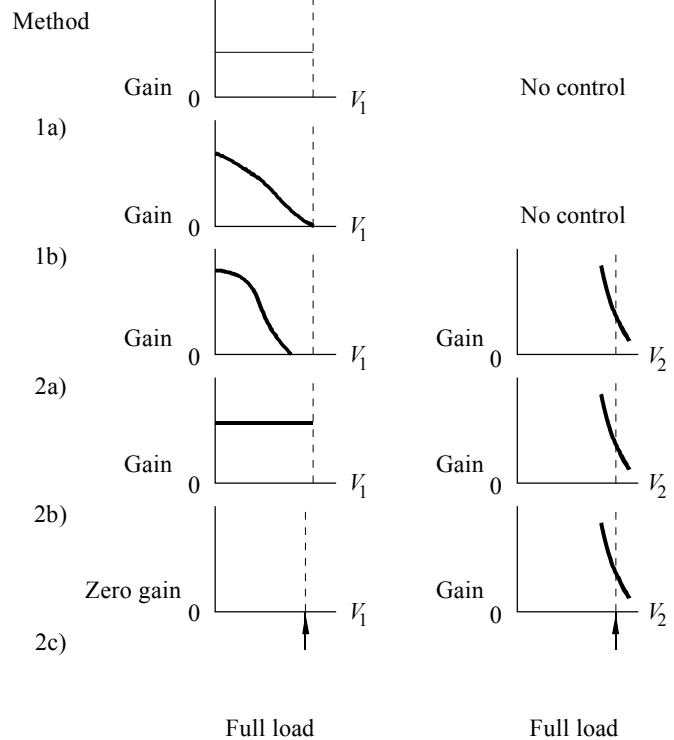
(Possible filters, buffer-amplifiers and gain-regulating pilots omitted)

To provide some basis for comparing the efficiencies of these waveforms, the maximum energy spectral density, which they produce when applied to an unmodulated carrier, has been calculated for an assumed 10% increase in occupied radio-frequency bandwidth. The results are plotted in Fig. 2, relative to that which would occur under the conditions of busy-hour loading; the curves of Fig. 2 have been designated A-D as described above. However some approximations have been made, as the problem of the relation between signal distortion and radio-frequency bandwidth limitation has been avoided by assuming:

–   Carson bandwidth occupancy (with peak-to-r.m.s. ratio of 12 dB) throughout;

–   that this bandwidth formula may also be applied to the sum of the signal and dispersed r.m.s. deviation when the dispersal is by noise band;

–   in other cases, that the occupied radio-frequency bandwidth is increased by the peak-to-peak dispersal deviation.

The errors so incurred are not thought to be large, and in any case should be in the same sense for all waveforms. As a further approximation, each type of dispersing waveform is represented in Fig. 2 by a single curve.

FIGURE 2

Energy dispersal for multi-channel telephony systems

D02
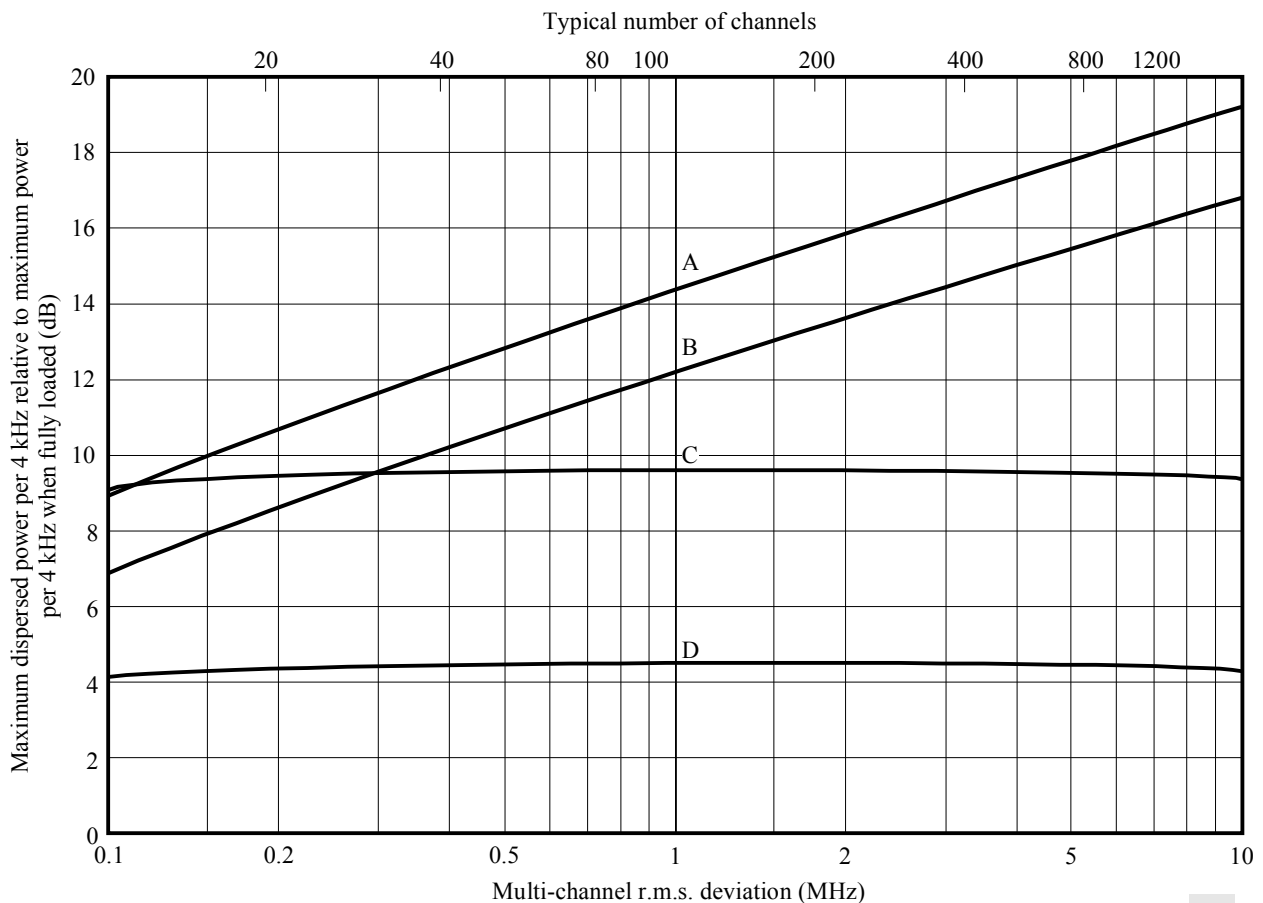
2.1.1.1 Sinusoidal dispersal

It is evident from Curve A of Fig. 2 that carrier energy dispersal by a sinusoidal signal is rather inefficient, while Curve B shows that a sinusoidal signal with 30% of third harmonic is only about 2 dB better. For a typical 20-channel transmission, the maximum power density in either case, exceeds that which occurs under full-loading conditions by about 10 dB. It is a feature of both these types of dispersal that the amount by which the dispersed power-density exceeds that at full loading, increases with the r.m.s. multi-channel deviation and hence with channel capacity. For example, the excess for 1 200 channels is about 18 dB.

2.1.1.2 Triangular dispersal

The most effective way, for a given increase in occupied bandwidth, of dispersing the energy present in a single spectral line is, at least theoretically, by the application of a triangular waveform. The dispersed power-density is inversely proportional to the permitted percentage increase in radio-frequency bandwidth and Curve D of Fig. 2 shows that, if a 10% increase in occupied bandwidth is permitted, the dispersed power per 4 kHz exceeds that under full-loading conditions by only about 4.5 dB for most numbers of channels.

When a low-frequency (≤ 1 kHz) triangular dispersal waveform is used on multi-channel systems, a wanted single-channel-per-carrier system can be exposed to nearly the full power of an interfering carrier for significant periods of time.

The triangular waveform evidently offers a simple and efficient means of dispersing the energy present in isolated spectral lines of telephony transmissions. It must be remembered, however, that its effectiveness depends upon faithful preservation of the shape of the wave until it appears as frequency-modulation, particularly when a high degree of dispersal is required. If 32 dB of dispersal were required for a 1 200-channel transmission, for example, flattening of the extremities of the wave by only 0.25% might lead to a local doubling of spectral energy density.

The triangular signal may have to be filtered before being applied, to prevent the harmonics of the fundamental from disturbing the lower channels of the telephone multiplex. For triangular waveform frequencies of up to 150 Hz and for a low frequency multi-channel baseband of 4 kHz, filtering causes deformation at the angles of the signal waveform and thus at the energy density peaks at the extremities of the modulation spectrum under light-loading conditions.

Table 1 shows measured values for the increase in energy density at the extremities of the spectrum in relation to the density at the centre frequency of the spectrum, for a 132-channel multiplex, as a function of the frequency of the triangular waveform. Discontinuous single step regulation was used for this system.

TABLE 1

Frequency of triangular waveform (Hz)	Increase in energy density (dB)
20	3
80	5
150	7

The low-pass filter used was a 7-pole Chebyshev-type filter with a cut-off frequency of 2.7 kHz and an attenuation at 4 kHz equal to 34 dB.

It is, however, possible to take account of the presence of the continuity pilot at the modulator input provided it is generated independently of the telephone multiplex. Under the same measurement conditions as indicated earlier, the application of a pilot at a level of −20 dBm0 makes it possible to reduce the energy density peaks at the extremities of the band from 7 to 3 dB.

2.1.1.3   Dispersal by a band of low-frequency noise

A form of carrier energy dispersal that is not critical in its application and shares with triangular dispersal the property of yielding a maximum energy spectral-density, inversely proportional to the amplitude of the waveform, may be accomplished by adding a band of low-frequency noise to the multi-channel baseband. Curve C of Fig. 2 shows that, for a 10% increase in occupied bandwidth, the maximum dispersed power per 4 kHz exceeds that under full-loading conditions by about 9.5 dB for all numbers of channels.

NOTE 1 – When the level of the dispersal signal is not fixed, the required amount of dispersion can be attained by other methods.

2.1.2   Method 1b)

An obvious variant of Method 1a) would incorporate an automatic means for adjusting the degree of artificial energy dispersal which would be applied according to the state of loading of the system, as shown in Method 1b) of Fig. 1. It might, in fact, be possible by using noise band dispersal in this way, to maintain the maximum energy spectral-density of a transmission quite close to its full-loading value without any increase in occupied radio-frequency bandwidth. The performance that could be achieved in practice, would depend on the distortion produced by the interaction (via radio-frequency bandwidth limitation and other transmission characteristics) of the dispersal waveform and isolated tones and active telephone channels under light-loading conditions. It is probable that the matter can only be settled experimentally, since there is as yet no generally accepted way of calculating the distortion that frequency-modulation signals undergo during transmission, even for the simplest case of white-noise loading.

A particular method which has been proposed for applying the variable degree of dispersal to which the present sub-section relates, relies on filling a suitable proportion of unoccupied telephone channels with simulated speech (i.e. band-limited noise). Although full dispersal could in this way be maintained without increase of bandwidth, the complexity of the apparatus likely to be required for the method is a serious disadvantage, as is the probable necessity for applying it at the audio switchboards from which the baseband originates.

2.2   Dispersal by automatic deviation control

2.2.1   General

It would clearly be possible to adjust the signal level entering the system frequency modulator so as to maintain the r.m.s. (or peak) frequency deviation at some constant value. The desired level could be obtained merely by subjecting whatever the baseband content happens to be, to sufficient amplification, or by so amplifying after the addition of some fixed or variable amount of artificial dispersal. The overall baseband transmission loss of the system would be kept sensibly constant by a compensating adjustment of the post-demodulation gain through the medium of a system pilot tone. The possibilities are discussed in the following paragraphs.

2.2.2 Method 2a)

The most general method of carrier energy dispersal of which the others are in a sense degenerate forms, is Method 2a) in Fig. 1. This consists in adding to the baseband, before the application of automatic deviation control, a source of artificial energy dispersal whose amplitude is made to depend upon the loading conditions. The use of this method might add little or nothing to the occupied radio-frequency bandwidth. Furthermore, if the application of artificial dispersal were delayed until the approach of light-loading conditions, a valuable decrease in the sensitivity of the system to thermal noise, distortion and interference might result. The magnitude of this decrease would depend upon what fraction of the fully-loaded baseband power was attributable to speech signals. As for Method 1b), some determination of the baseband distortion associated with this method is desirable, although, other things being equal, such distortion would be less than in the earlier method, because the increased deviation-per-channel under light-loading conditions would render the system less sensitive to the radio-frequency distortion components produced.

With regard to the choice of a means of artificial dispersal to be added to the baseband, this might consist of any of the low-frequency dispersal waveforms considered in § 2. The noise-band waveform resembling one or more perpetually active telephone channels is perhaps to be preferred, because it is moderately efficient and because it has the same dispersing effect for a given r.m.s. deviation as the baseband signal. It also allows accurate deviation control to be obtained by a simple r.m.s. detector and presents no difficulties of application at large amplitudes.

2.2.3 Method 2b)

As a trivial simplification of the foregoing method, the amplitude of the added dispersing waveform might be set at some fixed value. There would be some increase in occupied radio-frequency bandwidth, although not so much as in Method 1a) for the same degree of dispersal.

2.2.4 Method 2c)

The complete omission of artificial dispersing waveforms from the modulating signal would reduce dispersal by automatic deviation control to its simplest form. The effectiveness of the method would seem to depend on the baseband spectrum retaining some moderate degree of complexity even under light-loading conditions. Unfortunately, it may not be possible to count upon this; in the complete absence of telephone channel activity, the system loading would degenerate to a number of pilot tones, carrier leaks and the like. There might be enough of these in a large system to yield some semblance of evenly distributed baseband power, but this is unlikely to be true of low-capacity systems. In such systems, particularly if many of the carrier leaks were at an unusually low level, the lowest levels of loading might derive from a very small number of prominent pilots.

It can readily be shown that, if the loading of a system results from only one or two prominent tones in the baseband, the radio-frequency spectral-densities may exceed those obtained under full-load conditions by many decibels. It would, therefore, be unwise to rely upon the presence of a few tones to bring about, by application of automatic deviation control alone, a similar degree of energy dispersal to that which results from full-loading.

2.3   Summary

Considering the methods of application of the dispersal waveform, the use of Method 1a) would result in an undue increase in the occupied bandwidth if it were desired to approach the busy-hour loading conditions. Hence, Method 1b), which incorporates automatic means of adjusting the degree of dispersal applied according to the state of the loading of the system, offers a much more attractive arrangement.

Method 2 is more complicated than Method 1, but turns to advantage the need to provide energy dispersal by improving system noise performance when the deviation sensitivity is increased under light loading conditions. The obvious disadvantage of this method is the need to provide overall gain regulation, while the extent of the advantage which would accrue under conditions of light loading is dependent on traffic loading outside the busy periods of the day. Of the variants of Method 2 discussed in § 2.1, Method 2a) would seem to be the most suitable for general application.

With any method which requires the amount of added dispersal to be changed abruptly as the loading varies, careful attention must be paid to the choice of delay time between the change in loading and the time of switching the dispersal.

In considering the amount of dispersal which can be achieved in practice, it has to be borne in mind that the fully loaded condition will not necessarily provide the degree of dispersal postulated by a Gaussian distribution. It would be unwise to assume that, in practice, this ideal condition is attained, until there is some convincing support for such an assumption. It has been shown by practical measurements using white noise loading that systems which apply a triangular dispersal waveform can maintain the dispersal of carrier energy to within 2 dB of the dispersal under simulated fully busy-hour loading conditions. It is not yet known how closely this condition will be approached with actual traffic loading but it seems unwise to assume that the energy will be dispersed to within less than 3 dB of that applying with busy-hour load conditions, without some increase in radio-frequency bandwidth.

3   Energy dispersal techniques for use with analogue frequency modulation television signals

3.1   Introduction

In a television transmission system using frequency-modulation a large proportion of the radiated power may be concentrated on or near the radio carrier-frequency under certain modulation conditions, e.g. when a television picture with large areas of the same brightness is being transmitted. Energy dispersal can be achieved by adding a suitable low-frequency waveform to the video signal before modulation.

To obtain information on the degree of degradation which would be introduced when this type of energy dispersal technique is used, an experimental study has been made to determine the subjective effects, on 625-line monochrome television signals, of adding and removing, by several methods, various low-frequency waveforms which are suitable for energy dispersal purposes.

To determine the dispersal effect produced by this method, it will be assumed, for the purpose of example, that the overall system performance restricts the permissible peak-to-peak amplitude of the dispersal waveform to 30% of the peak-to-peak amplitude of the video signal. Considering a 625-line system employing the normal pre-emphasis network (Recommendation ITU-R F.405), this

peak-to-peak deviation of the dispersal waveform will be 9.4% of the peak-to-peak deviation of the video signal without pre-emphasis. Using the symbol ΔF in MHz for the peak-to-peak deviation of the video signal, the dispersal obtained is approximately:

$$10 \log \left(\frac{\text{maximum energy per 4 kHz}}{\text{total energy}} \right) = 10 \log \frac{0.004}{0.094 \, \Delta F} = - (14 + 10 \log \Delta F) \qquad \text{dB}$$

For comparison, the theoretical dispersal obtained in the telephony case (assuming a Gaussian spectral distribution and a peak-to-r.m.s. ratio of 12 dB as in § 2.1.1), is:

$$- \left(28 + 10 \log \frac{\Delta F}{8} \right) = - (19 + 10 \log \Delta F) \qquad \text{dB}$$

which means that the television case is likely to be only some 5 dB below optimum for some 10% increase in radio-frequency bandwidth.

In the interests of bandwidth economy, it would be desirable to be able to control the deviation on the lines of Method 1b) of § 2.1. It is not obvious that any simple method is possible as it would presumably be necessary to monitor the energy concentration in the radio-frequency spectrum.

In addition to the methods of energy dispersal discussed above, two other systems are described in § 3.5 and 3.6. The first describes dispersal by video transformation, the second describes dispersal techniques used to improve protection to SCPC telephony transmissions for which the dispersal signal has the frequency of the television line frequency. Section 3.6 also describes a composite energy dispersal technique where the dispersal signal consists of a triangular waveform at frame rate frequency and a waveform either triangular or sinusoidal at half-line rate frequency. This technique can be used to reduce the effects of the interference caused in both FDM telephone systems and SCPC carriers.

3.2 Dispersal waveform

The amplitude and shape of the dispersal waveform which is added to the video signal before modulation, must produce the required amount of carrier energy dispersal without introducing a significant degradation in the transmission performance of the system. This latter requirement also depends upon the efficiency of the method used to remove the added waveform and on the overall linearity of the transmission system. Two forms of triangular waveform (the "symmetrical" triangular and the "sawtooth" waveform), having repetition frequencies centred around 50, 25 and 12.5 Hz, have been considered in some detail to determine which waveform is to be preferred.

It was thought that the most favourable result would be obtained by synchronizing the dispersal waveform to the field-frequency of the television signal and also, that the relative phasing of the synchronized signals might, in some cases, give variations in picture impairment. These effects were examined by using both synchronized and unsynchronized dispersal waveforms and, as far as impairment to the received picture is concerned, the tests showed that there is a considerable advantage to be gained by using a synchronized, rather than an unsynchronized waveform. As the generation of waveforms synchronized to the television field-frequency presents no practical problems, the remaining experiments were confined to synchronized waveforms.

The process of synchronization should normally ensure correct phasing of the waveform with respect to the television field information. With the 50, 25 and 12.5 Hz "sawtooth" and the 25 and 12.5 Hz "symmetrical" waveforms, all points of inflection will occur during the field-blanking interval and the discontinuities in the slope of the waveform will not appear as an impairment to the

picture. With the 50 Hz symmetrical waveform, only alternate points of inflection can coincide with the field-blanking interval and the remaining points occur at the mid-point in each television field (i.e. across the middle of the picture).

It was thought likely that the peak-to-peak level of waveform which would be required for energy dispersal purposes, was between 10 and 50% of the peak-to-peak amplitude of the video signal before pre-emphasis, and the tests were confined to this range of levels.

A method of increasing the level of dispersal without, at the same time, increasing the peak frequency deviation has been proposed. In this method, the spikes formed at the edges of the video signal pulse as a result of the normal pre-emphasis network, are subjected to non-linear processing prior to modulation. This process decreases the peak-to-peak amplitude of the video signal, thereby providing the possibility of increased dispersal within the original bandwidth of the system.

A further factor to be taken into account in the design of dispersal systems is the likely presence of "natural" dispersal resulting from imperfections of system components. For example, systems involving up converters may introduce a significant level of dispersal as a result of "jitter" within the oscillators included in these units. Further study is required to determine what contribution "natural" dispersal may make to the problem of coordination, without at the same time introducing unacceptable reduction in system performance of the dispersed system.

3.3   Linearity of the transmission channel

When there are non-linearities in the transmission channel, intermodulation phenomena may appear between the dispersal waveform and the video signal. In such cases, there may be serious defects in the television picture, especially in colour pictures. For example, tests made with the PAL system and a symmetrical triangular dispersal waveform at 50 Hz (synchronized in the field scan) and about 0.5 V peak-to-peak amplitude, measured before pre-emphasis at a point where the video signal is at the nominal reference level (see Recommendation ITU-R F.270), showed that the subjective quality index of the picture was equal to 3 using a six-grade quality scale under the following conditions:

–   differential phase   8°

–   differential gain   10%

–   short-term non-linearity   10%.

It would seem advisable to continue the study of this subject, so as to determine the permissible limit of non-linearity for various television systems, in a satellite television link using energy dispersal.

3.4   Removal of dispersal waveform

At the receiving earth station, the dispersal waveform must be removed from the baseband signal, and the following methods have been proposed.

3.4.1   Waveform cancellation

The dispersal waveform can be removed from the baseband signal by "cancelling" it with a locally generated dispersal waveform which is added in anti-phase. It may be useful to transmit the dispersal waveform in a subsidiary channel as an alternative to regenerating the waveform locally.

Two methods of cancellation are possible. In the first method the dispersal waveform may be added in anti-phase, after demodulation. In the second method the local oscillator in the earth-station receiver is frequency modulated by the anti-phase dispersal waveform. This has the advantage that, since the energy dispersal is cancelled before demodulation of the frequency-modulation signal, no increase in the IF bandwidth is necessary. Recent experiments indicate that waveform cancellation followed by clamping (as described in § 3.4.2) is an effective method, and removes the dispersal waveform more completely than one or two stages of clamping alone.

3.4.2   Black-level clamping

The effects of the dispersal waveform may be removed from the baseband signal by using a well established television technique known as "black-level clamping". The "clamp" is a device which is normally used to remove low-frequency distortion from a television signal by means of a sampling and error correcting process.

The amount by which a low-frequency error-signal may be reduced by "clamping" is a function of the frequency of the error signal and of the level of random noise present on the video signal. As initial satellite systems may have to handle video signals having a poor signal-to-noise ratio, the characteristics of the clamps used in these experiments were adjusted to be consistent with the optimum performance which can be obtained with 625-line systems operating under conditions of poor signal-to-noise ratio. A typical characteristic for sinusoidal error-signals is given in Table 2.

TABLE 2

Error-signal frequency (Hz) (sine-wave)	50	25	12.5
$\dfrac{\text{Peak}-\text{to}-\text{peak error}-\text{signal output}}{\text{Peak}-\text{to}-\text{peak error}-\text{signal input}}$ (dB)	−15	−21	−27

(It should be noted that as the frequency of the error signal decreases, both the efficiency of the clamp and the visibility of flicker on a picture increase; on a subjective impairment basis, therefore, these two effects tend to cancel each other out.)

The effect of clamping an error signal having a triangular shape, produces a result which is similar to that which would be obtained if the error waveform were differentiated and with the levels which may be necessary in a practical energy-dispersal system, a single clamp of the type described does not reduce to an acceptable level the impairments introduced by any of the various waveforms under consideration.

At this point a major difference between the "sawtooth" and "symmetrical" waveforms should be mentioned. Because the slope of the "sawtooth" waveform is constant during the "active" part of each television field, the only impairment which may be observed on a picture monitor after the video signal has been clamped, is a slight, and probably insignificant shading across the picture. However, the very high slope of the dispersal waveform during the field-blanking interval causes a serious distortion of the waveform during this period, the magnitude of which is dependent upon the level of dispersal waveform being used. In practice, this distortion is most undesirable, as it can interfere with both synchronizing and vertical interval test signals which occur during the field-blanking interval. It is also extremely difficult to remove this form of distortion once it has been introduced into the video waveform.

With the "symmetrical" waveform, the residual impairment left after a single clamping operation can be observed as a picture impairment. With the 50 Hz waveform, the impairment appears as a disturbance across the middle of the picture. For the 25 and 12.5 Hz waveforms, a picture "flicker" can be observed. This effect is also dependent on the level of dispersal waveform being used, but the application of a further clamp will reduce the flicker effect to a level where it is imperceptible, even with a dispersal waveform amplitude of 50% of the peak-to-peak amplitude of the video waveform.

Although the characteristics of the waveform distortion left after twice clamping the signal are somewhat different in character, the magnitude of the residual distortion when a "symmetrical" dispersal waveform is used is some 10 to 20 dB less than when a "sawtooth" waveform is used.

3.4.3   Frequency feedback

The dispersal signal may be removed by the use of narrowband frequency feedback techniques applied to the IF stage of the receiver. This method has the advantage that it allows the effective receiver bandwidth to be reduced thereby improving the noise threshold of the receiver.

In a particular application of the above-mentioned principle, a dispersal signal of 2.5 Hz was selected. At the receiver the dispersal signal is removed by means of a negative feedback circuit containing a low frequency filter with a cut-off frequency lower than the lowest frequency of the video signal. The frequency deviation caused by the dispersal signal is thereby reduced by a value dependent on the degree of feedback employed, and a reduction of 15 dB is readily achievable, the amplitude of the video signal being unaffected.

3.5   Dispersal by video signal transformation

With angular modulation of the television signal, carrier energy dispersal can be provided by reversing the polarity of the video signal line by line and replacing line and frame synchronizing pulses by bursts of sinusoidal oscillations. The period of each burst is equal to that of the corresponding synchronizing pulse, and the peak-to-peak amplitude of the sinusoidal oscillation is equal to that of a video signal.

3.6   Line frequency energy dispersal waveform

Before reading the following text it should be noted that the use of line-rate energy dispersal requires further study in respect of the overall performance of the television chain for conventional composite analogue formats, and the impact on encrypted or component analogue formats.

The conventional television energy dispersal waveform i.e. a triangular wave at one-half the field frequency, is ineffective in providing protection for single-channel-per-carrier (SCPC) transmissions. This is because, with the resulting frequency sweep rate of about 1 MHz per 1/50 s, the time spent by the television carrier within the SCPC receive passband is much greater than the response time of the receiver IF filter. As a result the demodulator in the SCPC receiver is periodically exposed to the full television carrier power.

Studies in the United States of America, the Russian Federation and France indicate the possibilities of using energy dispersal at the television line rate to reduce the protection margin needed for PCM-PSK SCPC against FM-TV carriers by about 9-10 dB in comparison with one half-field frequency dispersal.

The use of a line frequency dispersal waveform will result in a level of interference to satellite and terrestrial radio-relay circuits of low modulation index FDM/FM carriers higher than would be caused by a low-frequency dispersal signal (frame frequency or less). The effect of this additional impairment would depend on the parameters of the systems concerned, and degradations of more than 7 dB have been observed.

In view of the interfering potential of FM-TV signals to SCPC systems and terrestrial radio-relay systems, it may be advantageous to use a composite dispersal signal with slow (e.g. frame frequency) and fast (e.g. line frequency) components.

Analytical studies as well as recent measurements have shown that in fact a mixed spreading waveform could even lead to lower requirements in terms of C/I compared to those obtained with a line rate dispersal only.

Measurements carried out with both triangular and sinusoidal waveforms as the fast spreading component lead to the conclusion that a mixed spreading system based on either of the two waveforms would exhibit similar performance.

The use of a sinusoidal waveform offers however advantages over that of a triangular waveform because the cancellation of a sinewave can be much easier than that of a triangular waveform. Hence even with the simple circuitry of low price home receivers, small values of residual energy dispersal waveform power can be expected, and the impairment on the quality of the television signal should be insignificant.

The adoption of a mixed energy dispersal modulation scheme consisting of a triangular component at Δf (half-line rate)/Δf (total) between 0.75 and 1 appears therefore a viable solution. Measurements have shown that the peak spectral density of the FM-TV signal is not increased if this scheme is used in replacement to other energy dispersal schemes, and therefore in this way the modulated FM-TV carriers can meet the power flux-density limits of the Radio Regulations. Further work is however required to provide a quantitative evaluation of the additional complexity which would be introduced in the receivers and on the subjective assessment of the quality of the television signal after the removal of the composite energy dispersal waveform.

For illustrative purpose Fig. 3 shows a method for the removal of the composite energy dispersal waveform, based on a conventional sample integrate/feedback type clamp to remove frame rate energy dispersal, supplemented by a sinusoidal half-line energy dispersal removal arrangement.

The peaks of the half-line component are arranged to fall at the line synchronization pulse points. Sampling at these points is used to monitor both components of the energy dispersal waveform.

The half-line removal circuit generates a half line-rate sinewave from the synchronization pulses. Its amplitude is controlled in a closed loop by processing samples of the output video signal so as to drive the residual half-line components to zero. A 180° phase ambiguity caused by the divide-by-two operation is removed by the bi-polar attenuator.

FIGURE 3

**Example of a method for the removal of a composite frame
rate/half line-rate energy dispersal waveform**
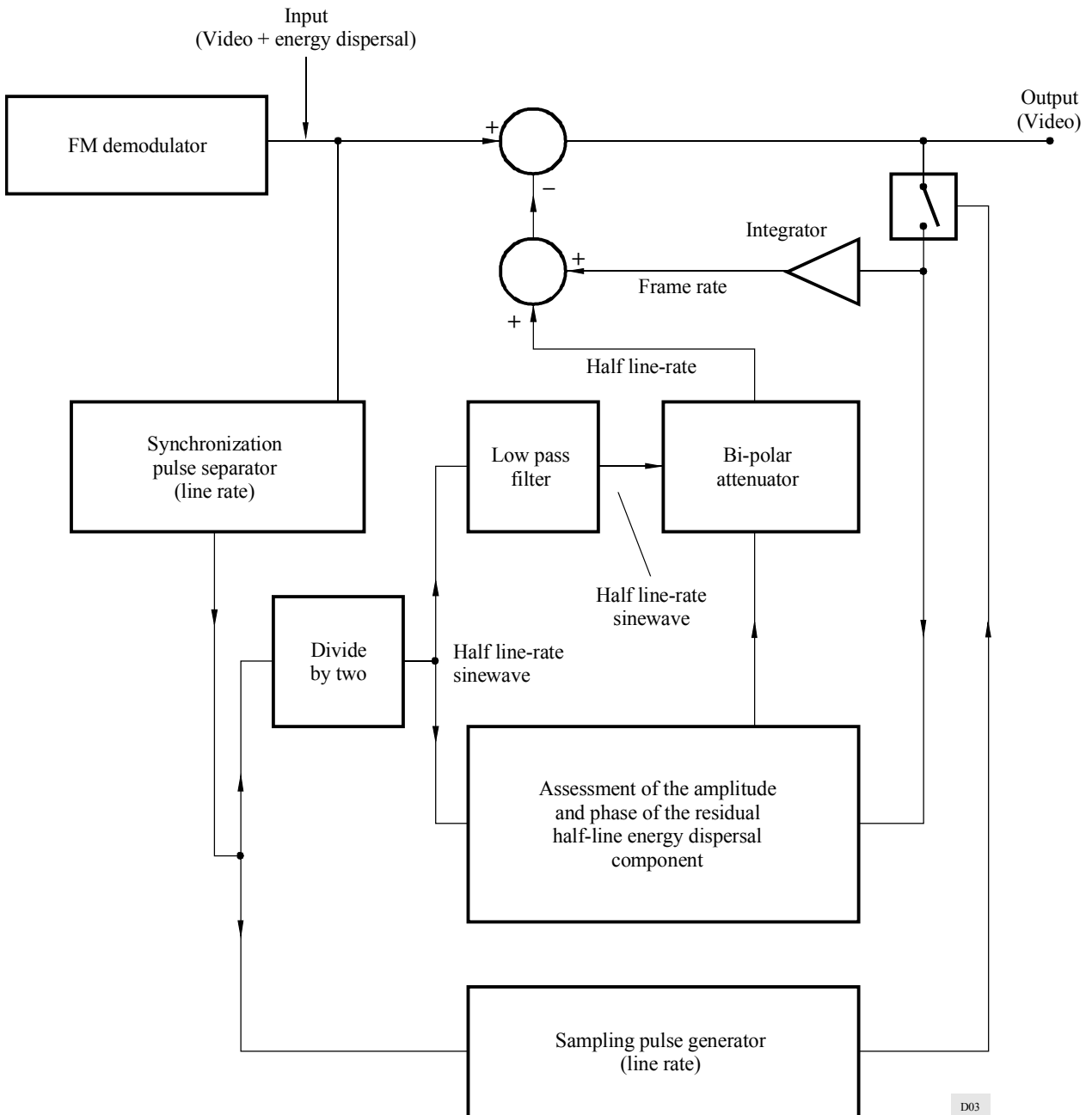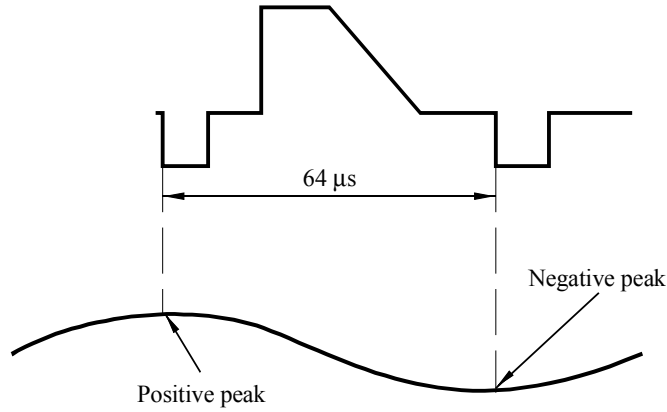
4 Energy dispersal techniques for use with digital signals

4.1 General

When the information pulse train has a random pattern, the energy of the RF carrier is sufficiently dispersed to reduce the peaks of the power flux-density at the surface of the Earth produced by emission from the space station. If, however, the information pulse train includes a fixed pattern having a periodic repetition rate, some line components appear in the spectrum of the RF carrier, and it follows that some of the peaks of the power flux-density at the surface of the Earth may exceed the level recommended by the ITU.

The purpose of the energy dispersal techniques described here is to reduce the peaks of the spectrum by producing a transmission pulse train similar to a random pattern, irrespective of any patterns in the information pulse train. Two methods of energy dispersal techniques are described in § 4.3.

4.2 Spectra of PSK digital signals

The power spectrum of a carrier modulated by ideal phase reversals consists of "lines" which for a pseudo-random sequence of N symbols of t seconds per symbol are separated by $1/Nt$ (Hz). The power spectrum of these lines is given approximately by the following equation:

$$W(f) \approx \frac{1}{N} \left\{ \frac{\sin \pi (f - f_c) t}{\pi (f - f_c) t} \right\}^2 \delta \left(f - f_c - \frac{n}{Nt} \right) \tag{1}$$

where:

N: length of the pseudo-random sequence (symbols)

t: symbol duration (s)

n: integer

f_c: RF carrier frequency (Hz)

δ: delta function.

The largest line is at $n = 1$.

As the sequence length approaches infinity, $N \to \infty$ then $Nt \to \infty$, and the "line" separation $\to 0$. In this case the power spectrum becomes continuous and thus:

$$W(f) = t \left\{ \frac{\sin \pi (f - f_c) t}{\pi (f - f_c) t} \right\}^2 \quad \text{per Hz} \tag{2}$$

In this case, it is seen that the maximum spectral-density occurs at the carrier frequency.

Equation (2) shows the mean value of the power spectrum with the idealized situation of a random pulse train. The actual modulating signal may be far from random. For example, in the case of PCM telephony employing 8 bits per sample, there is likely to be considerable periodicity at one-eighth of the bit rate, and during periods of light traffic loading the situation could arise that the transmitted signal consists almost entirely of zeros. Under these conditions the PSK spectrum will have much of its power concentrated into one, or a few, spectral lines and the dispersal factor could approach 0 dB.

In addition to the non-randomness in the information part of the signal there will also be repetitive patterns in the preambles of time division multiple access (TDMA) transmissions.

Also, in a practical system, the spectrum will be modified by pulse phasing and/or post-modulator filtering. However, this will have greatest effect towards the edges of the spectrum and the maximum spectral-density will not be greatly affected.

To ensure a desired degree of dispersal a pseudo-random sequence of $N\ t$ duration can be modulo-2 added to the information bit or symbol stream, as shown in Fig. 4.

For a reference bandwidth of 4 kHz, an energy dispersal factor (D) may be defined as:

$$D = 10 \log \frac{\text{total power}}{\text{maximum power per 4 kHz}} \qquad (3)$$

When a pseudo-random sequence is utilized for energy dispersal the degree of dispersal can be estimated by equations (1) and (3) when $1/N\ t \geq 4$ kHz and by equations (2) and (3) when $1/N\ t < 4$ kHz.

As it is indicated by the preceding equations, the degree of dispersal is proportional to N as long as the sequence duration is less than the reciprocal of the reference bandwidth. There is little additional dispersal to be gained after the sequence duration reaches 250 µs (4 kHz reference bandwidth).

4.3   Energy dispersal techniques

4.3.1   Method 1: Pseudo-random scrambler

This method consists of maintaining the transmission pulse train in a state similar to that which it would have for a random pattern, irrespective of channel occupancy, by synthesizing a pseudo-random sequence from the information pulse train generated in a pseudo-random code generator using an exclusive OR circuit (Modulo-2 Adder). A schematic diagram of an energy dispersal circuit of the transmitting unit is shown in Fig. 4a). In a receiving unit a pseudo-random code generator, generating the same code pattern as that in the transmitting unit, recovers the original information by synthesizing the pseudo-random code sequence, generated by the pseudo-random code generator, with the transmission pulse train in an exclusive OR circuit. Figure 4b) shows a schematic diagram of such a receiving unit.

One of the merits of this technique is that the energy-dispersal can be achieved without any degradation of the quality of the information pulse train. On the other hand, a disadvantage of this technique is that it necessitates the synchronization of the pseudo-random code generator in the receiving unit with the pseudo-random code generator in the transmitting unit. However, in the case of TDMA systems, the synchronization between both pseudo-random code generators can be effected by utilizing the burst synchronization signal already provided by the receiving unit, hence no additional device will be needed for synchronization.

It should be noted that the symbol (or "chip") rate of the pseudo-random sequence need not necessarily be equal to that of the information pulse train.

Experimental digital television transmissions via satellite have been conducted and the energy dispersal factor has been measured. With a 60 Mbit/s 4-PSK signal and an 11 stage pseudo-random scrambling sequence the measured energy dispersal factor was 37 dB. The theoretical optimum dispersal with this type of signal would be 38.7 dB.

4.3.2   Method 2: Self scrambler

In this energy dispersal technique, shift registers having a feedback loop and a feedforward loop are installed in the transmitting and receiving units, respectively. In the transmitting unit a code conversion is performed for each bit of the information pulse train. At the receiver, each bit of the transmission pulse train is reconverted to recover the original information pulse train. Typical circuit arrangements of such scramblers and descramblers are shown in Figs. 5a) and 5b) respectively.

FIGURE 4

An example of energy-dispersal circuits using Method 1
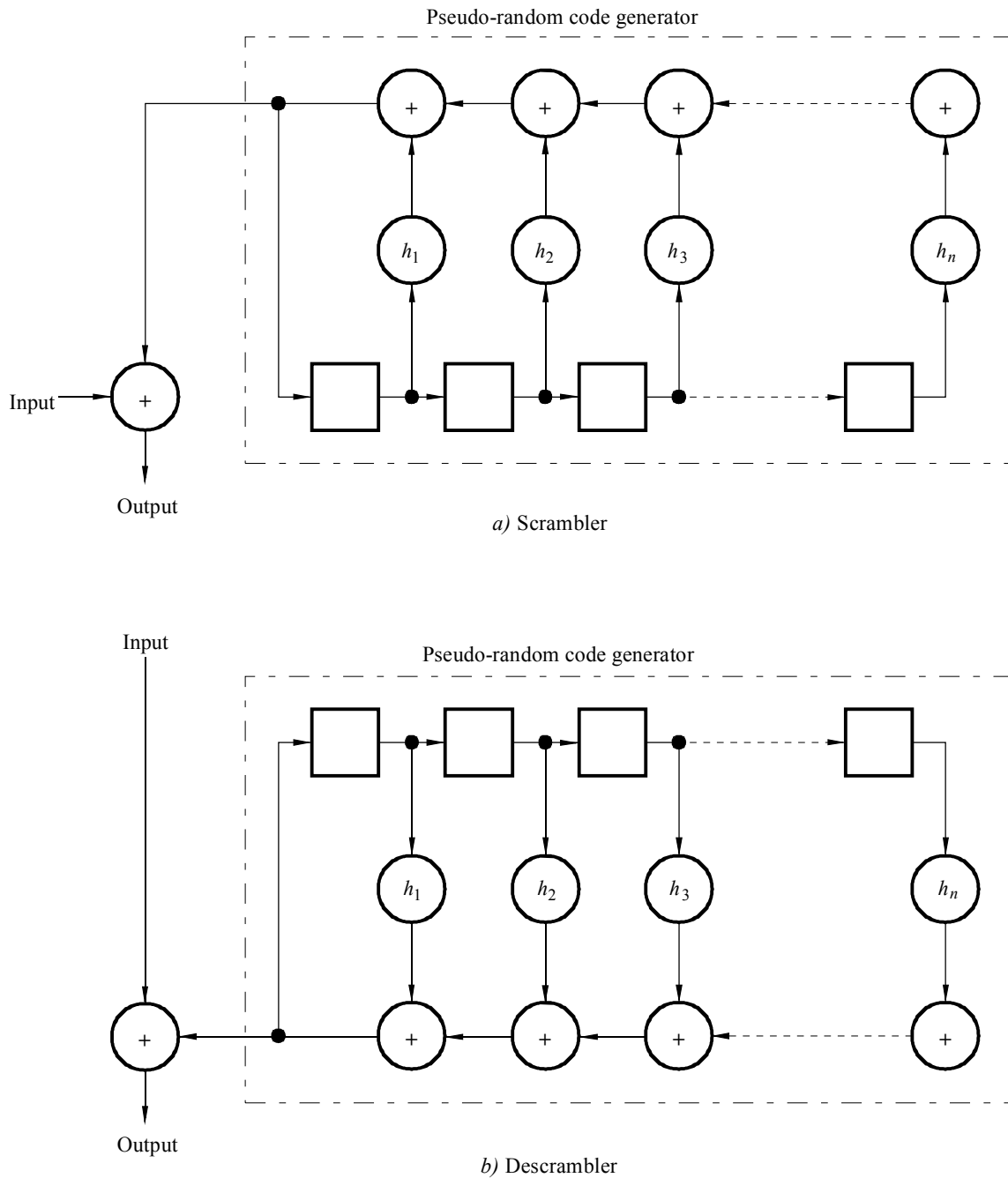
a) Scrambler

b) Descrambler

Note 1 − h_1, h_2 ... h_n represent the shift register internal connections which determine the code sequence.

D04

FIGURE 5

An example of energy-dispersal circuits using Method 2
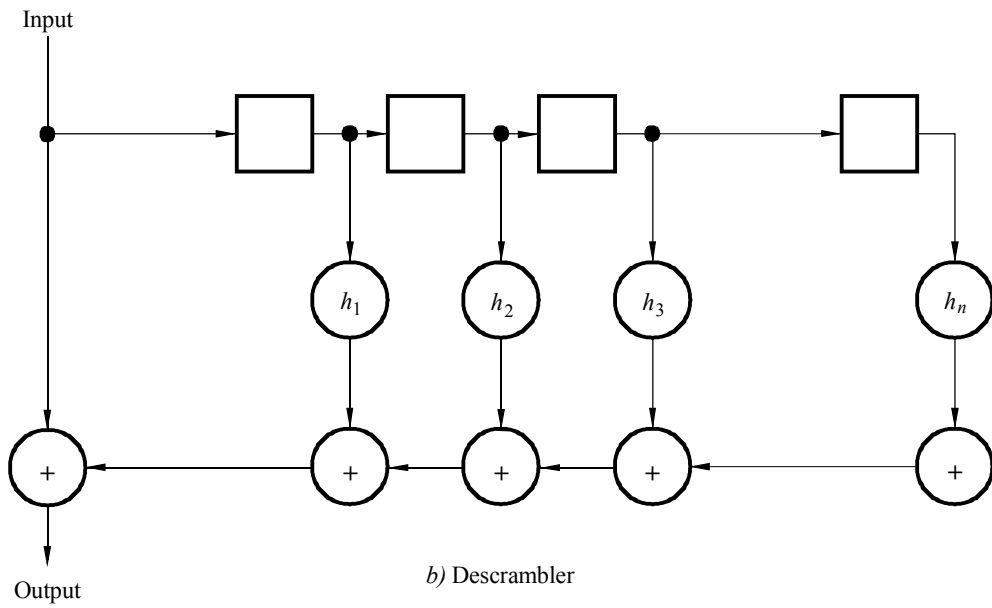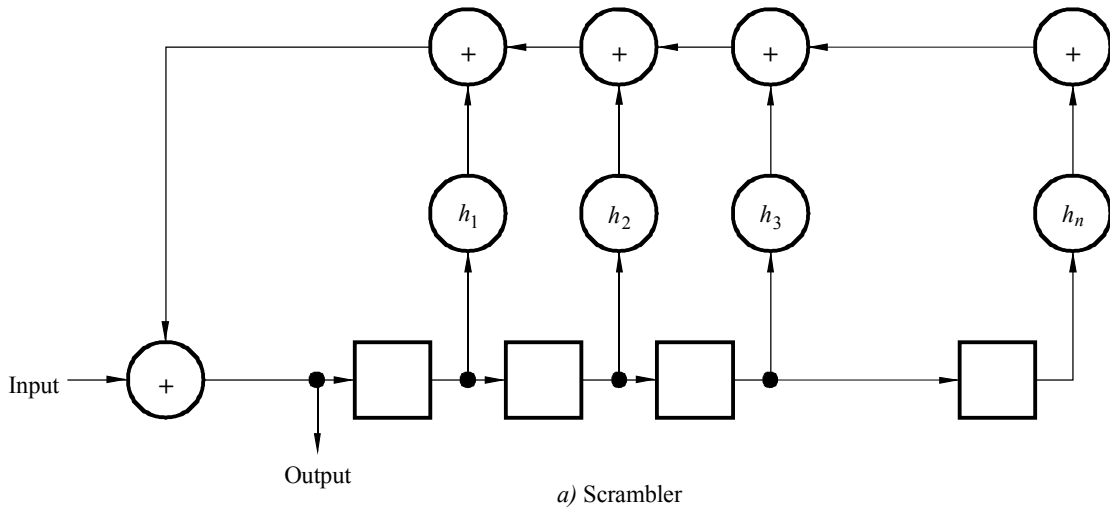
a) Scrambler

b) Descrambler

Note 1 – h_1, h_2 ... h_n represent the shift register internal connections which determine the code sequence.

D05

One of the merits of this energy dispersal method is that no synchronization is needed between the scrambler and the descrambler. On the other hand, there is a disadvantage in that, if *r* is the number of the stages of the shift register, the initial state of this register affects the first *r* bits of the transmission pulse train and consequently a single bit error in the RF transmission channel affects the *r* bits immediately following the error bit. This method, however, can be used together with error detection and correction; and it may represent a suitable energy dispersal method for use in PCM data transmission systems, especially those operating in the continuous mode as distinguished from the TDMA mode.

4.4 Energy dispersal factor for TDMA systems

The degree of dispersal obtained by Method 1 is directly proportional to the length of the pseudo-random sequence. However, there is no point in using a sequence which is greater than 250 µs in duration since the spectral lines in the dispersed spectrum would then be at less than 4 kHz separation. In a TDMA system the pseudo-random signal generated at the receiver can be most readily synchronized with that at the transmitter, if the sequence starts again from the beginning in every TDMA burst. This means that sequence lengths will usually be less than 250 µs and that the ideal dispersal will not be achieved.

The energy-dispersal effects for a TDMA signal depend on the length of the pseudo-random sequence, the frame length, the number of the bursts, the length of each burst, the scrambler methods and so on. If it is assumed for the sake of simplicity, that the length of each burst is equal to, or less than, 250 µs, and that each burst is scrambled by the same pattern of the pseudo-random sequence in every frame, the energy dispersal factor (D) can be given approximately by the following equations:

$$D = 10 \log N + 10 \log B - K \qquad \text{when } N < M \qquad (4)$$

$$D = 10 \log M + 10 \log B - K \qquad \text{when } N > M \qquad (5)$$

where:

N: length of the pseudo-random sequence (symbols)

M: length of the information sequence (symbols)

B: number of the bursts in one frame

K: margin for the energy-dispersal effect.

In the above equations, K is the statistical variation term indicating the decreasing degree of the energy dispersal effects caused by:

– the effect of the partial coincidence between an information sequence and a pseudo-random sequence;

– the effect of the difference between the length of the information sequence and that of the pseudo-random sequence;

– the effect of the carrier phase coherency between the bursts.

Among these effects, the first can be evaluated as follows: when the information sequence has weak frame correlation, the margin due to partial coincidence depends on the observation period of the power spectrum. On the other hand, when the information sequence has strong frame correlation, almost the same sequence pattern would be generated in every frame, so that its margin can be estimated by regarding the frame period as the observation period mentioned above.

The second effect could be made negligibly small by properly choosing the degree and the initial value of the pseudo-random sequence, if the length of the pseudo-random sequence is less than several times that of the information sequence.

The third effect is also negligibly small, since the carrier frequency of each burst is usually different by more than several hundred Hz from the adjacent bursts.

Clearly, the complexity of the system is greatly reduced if the pseudo-random sequence is applied only to the information part of the signal and not to the preamble of a TDMA burst. Generally the preamble will consist, at least in part, of a simple repetitive pattern. In some cases, it may even contain a period of unmodulated carrier. The results presented in Table 3, show that for a repeated

0011 preamble pattern in a 4-phase PSK system, the preamble will not contribute significantly to the maximum spectral-density except perhaps for low bit rate systems. Other preamble patterns having the same duration as that assumed for Table 3 would be no more than 3 dB worse.

To illustrate what dispersal factors might be achieved in practice, Table 3 shows the values for a TDMA system in which the preamble is not dispersed. Certain assumptions were made as follows:

–   frame length, 125 μs;

–   modulation, 4-phase PSK;

–   preamble signal, 40 bits of alternating 0011;

–   carrier frequencies of all stations are within 4 kHz of each other, but the symbol timing of different stations is not necessarily in phase;

–   pseudo-random sequence generators are reset after every burst.

TABLE 3

Illustrative energy-dispersal factors for a range of pseudo-random sequence lengths

	Single access Dispersal factors (dB)			10 equal station access Maximum power in a 4 kHz band (dB relative to total steady power)						Resultant dispersal factors (dB)		
				a) due to preambles			b) due to information					
Bit rate (Mbit/s)	10	50	250	10	50	250	10	50	250	10	50	250
Random modulating signal	31	38	45							31	38	45
127 bit pseudo-random sequence	12	12	12	−23	−37	−51	−20	−22	−22	20	22	22
511 bit pseudo-random sequence	18	18	18	−23	−37	−51	−20	−28	−28	20	28	28
2 047 bit pseudo-random sequence	24	24	24	−23	−37	−51	–	−29	−34	–	29	34
32 767 bit pseudo-random sequence	25	32	36	−23	−37	−51	–	–	−36	–	–	36
Typical fully loaded FM system occupying same bandwidth as the digital system (based on Gaussian spectrum and a ratio of RF bandwidth to baseband width equal to 15)	27	34	41									

Statistical variation of the power spectrum is such that 1% of the spectral lines will exceed the r.m.s. envelope by 6.5 dB.

The calculation of maximum spectral power density determined by preambles in the 4 kHz band shows that in some situations with a relatively high frame or packet preamble content and large earth station networks (for systems using variable-duration packets) the sync signal spectral power density may exceed the corresponding spectral power density of the information part of the signal. This phenomenon is more pronounced at low bit rates and long frame durations.

4.5 An example of energy dispersal applied to an experimental TDMA system

Method 1 energy-dispersal techniques were utilized in the TTT system, an experimental, 50 Mbits/s TDMA system developed in Japan for use in satellite radiocommunications systems. In this system, only the information bits are scrambled, yet it was found that the peak value of the power spectrum was suppressed by about 20 dB.

It should be noted that when energy dispersal using a pseudo-random sequence is applied to a TDMA system, the probability of false detection of a given "unique word" may increase to an extent depending on the manner in which the burst is synchronized.

False detection of the unique word can be avoided by changing the initial state of the pseudo-random sequence for every frame.

5 Conclusions

It appears that the most promising methods of energy dispersal are as follows:

– for frequency-modulation telephony systems: the addition of a signal below the baseband, controlled according to the loading as in Method 1b) of Fig. 1. The controlled signal may be noise or a "symmetrical" triangular waveform but the actual implementation is generally easier with the latter;

– for frequency modulation television systems: the addition of a "symmetrical" triangular waveform, synchronized to the picture frequency as in Method 1a) of Fig. 1;

– for digital modulation systems: code conversion by which the message bit stream is multiplied by a pseudo-random pulse train, using methods similar to those outlined in § 4.

Currently triangular dispersal waveforms are applied to frequency modulated carriers in most fixed satellite networks. The extent to which the theoretical advantage of triangular dispersal waveforms is approached in practice depends on the linearity of the waveform used. The use of these methods could provide energy dispersal as great as that provided under full-load conditions. However, the excess of the dispersal power per 4 kHz over that achieved under full-loading conditions (assuming a Gaussian spectrum), is unlikely in practice to be less than 3 dB for telephony and 5 dB for television. With this level of energy dispersal the addition to the radio-frequency bandwidth occupied, has not presented any difficulties.

The energy dispersal currently being obtained from triangular dispersal waveforms is proving satisfactory in practice except when the wanted signal is a single-channel-per-carrier system. With the use of low frequency (≤ 1 kHz) triangular dispersal waveform on multi-channel systems, a wanted single-channel-per-carrier system can be exposed to nearly the full power of an interfering carrier for short periods. This problem might be overcome in frequency modulated television systems, by using video signal transformation for dispersal, or by using a triangular dispersal waveform at the television line frequency.