

SECTION 4/9B: CO-ORDINATION AND INTERFERENCE CALCULATIONS

RECOMMENDATION 766

METHODS FOR DETERMINING THE EFFECTS OF INTERFERENCE ON THE PERFORMANCE
AND THE AVAILABILITY OF TERRESTRIAL RADIO-RELAY SYSTEMS
AND SYSTEMS IN THE FIXED-SATELLITE SERVICE

(Questions 32/4 and 109/9)

(1992)

The CCIR,

considering

- a) that it is necessary to evaluate the effects of interference on the performance and the availability of terrestrial radio-relay systems and systems in the fixed-satellite service;
- b) that, in general, the determination of interference criteria requires suitable calculation methods;
- c) that calculation methods for determining interference to FDM-FM systems are fairly well established;
- d) that calculation methods for interference to single-channel-per-carrier (SCPC) FM telephony are to be established;
- e) that calculation methods for interference to FM television are to be established;
- f) that calculation methods for interference to amplitude modulated (AM) telephony are to be established;
- g) that calculation methods for interference to digital transmissions are to be established;
- h) that, in future, calculation methods for interference to systems employing new modulation techniques may need to be established;
- j) that it is desirable to provide spectra of signals for determination of interference from the general formulation,

recommends

- 1. that the methods described in Annex 1 be used for calculation of interference to FDM-FM systems;
- 2. that in the absence of more accurate information the methods described in Annex 2 be used provisionally for wanted signals other than FDM-FM.

ANNEX 1*

Calculation methods for the interference of FDM-FM systems

Given below is the method of calculation to determine the effects of interference to the FDM-FM systems in terrestrial radio-relay systems and systems in the fixed-satellite service.

* *Note from the Director, CCIR* – For information, derivation of the formulae and historical development of this Annex are given by References contained in CCIR Report 388 (Düsseldorf, 1990).

1. Calculation methods

1.1 General formulation

The relationship (this linear relationship is only valid for the lower levels of interference into FDM-FM telephony signals) between baseband interference power in a telephone channel and the carrier-to-interference ratio involves the interference reduction factor B (in dB), defined as follows:

$$B = 10 \log \frac{S/N_i}{C/I} \quad (1)$$

where:

S : test signal power in a telephone channel = 1 mW

N_i : unweighted interference power in a telephone channel (bandwidth: 3.1 kHz)

C : power of the wanted signal carrier (W)

I : power of the interfering signal carrier (W).

The weighted interference power N_p (pW) is obtained as unweighted power in 1.75 kHz, which gives:

$$10 \log N_p = 87.5 - B - 10 \log (C/I) \quad (2)$$

The interference reduction factor B is expressed as:

$$B = 10 \log \frac{2(\delta f)^2 p(f/f_m)}{b f^2 D(f, f_0)} \quad (3)$$

with:

$$D(f, f_0) = \int_{-\infty}^{+\infty} S(F) P_1(f + f_0 - F) dF + \int_{-\infty}^{+\infty} S(F) P_1(f - f_0 - F) dF + S(f + f_0) P_{10} + \\ + S(f - f_0) P_{10} + S_0 P_1(f + f_0) + S_0 P_1(f - f_0) + \frac{S_0 P_{10}}{b} \delta(f - f_0) \quad (4)$$

$$P_1(f) = P(f) A^2(f) \quad (5)$$

$$P_{10} = P_0 A^2(0) \quad (6)$$

$$\begin{aligned} \delta(f - f_0) &= 1 & \text{when} & & f &= f_0 \\ \delta(f - f_0) &= 0 & \text{when} & & f &\neq f_0 \end{aligned} \quad (6a)$$

where:

δf : r.m.s. test tone deviation (without pre-emphasis) of the wanted signal (kHz)

f : centre-frequency of channel concerned, within the wanted signal baseband (kHz)

f_m : upper frequency of the wanted signal baseband (kHz)

$p(f/f_m)$: pre-emphasis factor for centre-frequency of channel concerned, within the wanted carrier baseband

b : bandwidth of telephone channel (3.1 kHz)

f_0 : separation between carriers of the wanted and interfering signals (kHz)

$S(f)$: continuous part of the normalized power spectral density of the wanted signal with pre-emphasis (Hz⁻¹)

S_0 : normalized vestigial carrier power of the wanted signal

$P(f)$: continuous part of the normalized power spectral density of the interfering signal (Hz⁻¹)

P_0 : normalized vestigial carrier power of the interfering signal

$A(f)$: amplitude-frequency response of the wanted signal receiving filter, the origin of the frequencies being the centre frequency of the interfering signal carrier.



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The power spectral densities are normalized to unity and are assumed to be one-sided (only positive frequencies).

The expression of N_p in terms of the ratio C/I is derived from expressions (2) and (3). In order to determine N_p , it is necessary to determine:

- the wanted signal spectrum (analogue telephony),
- the interfering signal spectrum.

The expressions of these spectra are given in § 2 below and in § 3 of Annex 2.

1.2 Interference from a low-modulation-index FDM/FM signal to a high-modulation-index FDM-FM signal

This case represents a terrestrial radio-relay system interfering into a system of the fixed-satellite service. The baseband channel which receives the most interference is not easily identified. However, the worst interference condition results when the wanted-to-unwanted carrier frequency separation is equal to, or less than, the top baseband frequency of the wanted signal.

The factor B can be determined from the following formula:

$$B = 10 \log \frac{1}{b f^2} \left\{ \frac{2(\delta f)^2 p(f/f_m)}{S(f_0 - f) + S(f_0 + f)} \right\} \quad (7)$$

If the modulation index of the wanted signal is greater than 3, the signal spectrum shape is near Gaussian, and formula (7) takes the following form:

$$B = 10 \log \frac{1}{b f^2} \left\{ \frac{2\sqrt{2\pi} (\delta f)^2 p(f/f_m) f_s}{\exp \left[\frac{-(f_0 - f)^2}{2f_s^2} \right] + \exp \left[\frac{-(f_0 + f)^2}{2f_s^2} \right]} \right\} \quad (7a)$$

The definitions of the parameters in formulae (7) and (7a) have been given in § 1.1 with the exception of the following:

$$\begin{aligned} f_s : & \text{ r.m.s. multi-channel deviation of the wanted signal (kHz)} \\ & = \delta f \cdot 10^y \cdot (LF)^{1/2} \end{aligned} \quad (8)$$

LF : load factor, which is less than unity when not in the busy hour;

$$\begin{aligned} y &= (-15 + 10 \log N_c)/20 & \text{for } N_c \geq 240 \\ &= (-1 + 4 \log N_c)/20 & \text{for } 60 \leq N_c < 240 \\ &= (2.6 + 2 \log N_c)/20 & \text{for } 12 \leq N_c < 60 \end{aligned} \quad (9)$$

N_c : number of voice channels in the baseband.

1.3 Interference from a high-modulation-index FDM-FM signal to a high-modulation index FDM-FM signal

The same comments as in § 1.2 apply concerning the baseband channel with the most interference and the worst frequency separation. Moreover, the factor B is identical to that given in formula (7) of § 1.2 with substitution of F_s for f_s .

F_s is defined as follows:

$$F_s = \sqrt{f_{s1}^2 + f_{s2}^2} \quad (10)$$

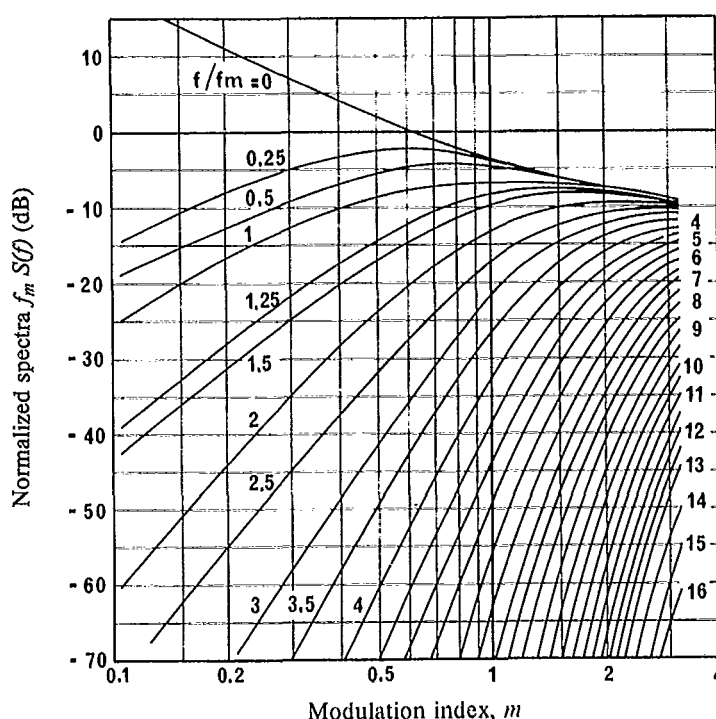
where f_{s1} and f_{s2} are the r.m.s. multi-channel frequency deviations of the wanted and interfering signals (kHz).

1.4 Interference between FDM-FM signals with intermediate modulation indices

Figure 1 contains a number of curves of normalized spectra as a function of the modulation index for given normalized frequency values. These curves may readily be used to plot the spectrum graph for any modulation index from 0.1 to 3. When $m > 3$, the signal spectrum shape is near Gaussian. If the modulation indices of the wanted and interfering signals are greater than 3, formula (7) should be applied to calculate interference, taking into account § 1.3.

In certain special cases, where the interfering signal may be characterized by its r.m.s. modulation index, and the upper baseband frequency is equal to the wanted signal (i.e. $f_{m1} = f_{m2} = f_m$) there is the possibility of calculating the interference function, $D(f, f_0)$, very simply from the normalized curves of Fig. 1.

FIGURE 1
Normalized spectral density of FDM-FM signals



The equivalent modulation index is determined by:

$$m = \left[m_1^2 + m_2^2 \right]^{1/2} \quad (11)$$

and for this value of m on the curves in Fig. 1 we find the values $f_m S(f_1)$ and $f_m S(f_2)$,

where:

$$f_1 = \frac{(f_0 + f)}{f_{m_1}} \quad \text{and} \quad f_2 = \frac{(f_0 - f)}{f_{m_1}} \quad (12)$$

and further:

$$D(f, f_0) = \frac{1}{f_{m_1}} [f_m S(f_1) + f_m S(f_2)] \quad (13)$$

The same method may be used for the approximate determination of $D(f, f_0)$ according to the value of the "equivalent" modulation index:

$$m = \left[m_1^2 + m_2^2 \left(\frac{f_{m_2}}{f_{m_1}} \right)^2 \right]^{1/2} \quad (14)$$

when:

$$f_{m_2} < f_{m_1} \quad \text{and} \quad m_2^2 \left(\frac{f_{m_2}}{f_{m_1}} \right)^2 \ll m_1^2 \quad (15)$$

The symbols used are defined as follows:

f_0 : carrier frequency separation

f_{m_1}, f_{m_2} : mid frequency of the top baseband channel of the desired and interfering signals respectively

m_1, m_2 : r.m.s. modulation indices of desired and interfering signal respectively.

1.5 Interference from a high-modulation-index FDM-FM signal to a low-modulation-index FDM-FM signal

This case is typically that of a system in the fixed-satellite service causing interference in a terrestrial radio-relay system. Low-index angle modulation can be regarded as quasi-linear with respect to some types of interfering signal; the calculation of interference in these cases is performed by a simple procedure analogous to that employed for linear DSB-AM.

The following approximate formula can be used:

$$\left\{ \frac{\text{Interference power in telephone channel}}{\text{Thermal noise power in telephone channel}} \right\} = \left\{ \frac{\text{Interfering signal power in two appropriate 4 kHz bands at the receiver input}}{\text{Thermal noise power in same two 4 kHz bands at the receiver input}} \right\} \quad (16)$$

1.6 Interference from angle-modulated digital signals into FDM-FM signals

Digital systems using PSK or FSK modulation are classes of angle-modulated systems. Consequently, the interference from these systems into analogue, angle-modulated systems is computed by the convolution integral. However, the spectral densities of digital, angle-modulated signals cannot be easily generalized; a specific spectrum is, however, provided in § 3.2 of Annex 2. More generalized computation would involve the calculation of the digital spectral density (see § 3.2 of Annex 2), the calculation of the analogue spectral density, the convolution of the two densities, and the computation of the factor B .

When a high-modulation-index FDM-FM carrier receives interference from angle-modulated digital signals that occupy a bandwidth small compared with that of the wanted signal, factor B is given roughly by formula (7).

If a wanted FDM-FM signal suffers interference from an unwanted PCM-PSK or DPSK-PM signal that occupies a bandwidth which is large compared with that of the wanted signal, factor B is given by the following simplified formula:

$$B = 10 \log \frac{1}{b f^2} \left\{ \frac{2(\delta f)^2 p(f/f_m)}{P(f_0 - f) + P(f_0 + f)} \right\} \quad (17)$$

The normalized spectral power density of the interfering signal $P(f)$ used in this formula is determined by the formulae (36a - 36d) given in § 3.2 of Annex 2.

1.7 Interference from AM signals into FDM-FM signals

The quasi-linear properties of low-modulation-index angle-modulated signals with respect to interfering signals whose spectral densities do not exhibit excessive variations within the receiver passband, permit the use for such cases of the following approximate formula:

$$\left\{ \frac{\text{Interference power in telephone channel}}{\text{Thermal noise power in telephone channel}} \right\} = \left\{ \frac{\text{Interfering signal power in two appropriate 4 kHz bands at the receiver input}}{\text{Thermal noise power in same two 4 kHz bands at the receiver input}} \right\}$$

Two 4 kHz bands are used in the formula since there may be asymmetry of the interfering spectrum with respect to the wanted carrier. When a high-modulation-index angle-modulated system receives interference from amplitude-modulated digital signals that occupy a bandwidth small compared with that of the wanted signal, factor B is given roughly by the formula of § 1.2.

1.8 Interference from a narrow-band system into an FDM-FM system

The theoretical expression of § 1.1 can be applied to the case of an interfering signal of arbitrary modulation, but with a bandwidth small compared with that of the interfered-with signal. Interference from SCPC to FDM-FM signals is an example of such a situation.

In particular, for evenly spaced SCPC carriers, the aggregate interference power in the baseband from all SCPC interference entries from one interfering network is close to thermal noise with equal power starting from five to six carriers.

1.9 Interference from FM-TV signals into FDM-FM signals

When the FM-TV signal modulated only by the dispersal waveform is the interfering signal, the FDM-FM wanted signal with a low number of telephone channels has a spectrum with a width commensurate with that of the interfering signal spectrum, and the carrier frequencies coincide, then formula (4) takes the form:

$$D(f, 0) = P \left[\int_{f-\Delta f/2}^{f+\Delta f/2} S(F) dF - \int_{f+\Delta f/2}^{f-\Delta f/2} S(F) dF \right] = 2P \int_{f-\Delta f/2}^{f+\Delta f/2} S(F) dF \quad (18)$$

where:

Δf : frequency deviation of dispersal waveform (peak-to-peak)

P : spectral power density of interfering signal (see Fig. 4, $i = 1$)
 $= 1/\Delta f$.

In the conditions described above, and with reference to formula (3), we may consider that:

$$\int_{f-\Delta f/2}^{f+\Delta f/2} S(F) dF \approx 1 \quad \text{when} \quad f < f_{m_1} \quad (19)$$

so that:

$$B = 10 \log \frac{(\delta f)^2 \Delta f p (f/f_m)}{f^2 b} \quad (20)$$

1.10 Residual tone interference of FDM-FM system with low modulation index

Special attention should be given to the severe effects of tone interference due to the residual carrier in FDM-FM systems with a low modulation index. The interference noise power $P_{\epsilon\delta}$ at the point of zero relative level is given by:

$$P_{\text{es}} = \frac{1}{2m_1^2} 10^{\frac{1}{10}y} \sum_{n=1}^{\infty} \frac{k^{2n}}{n^2} D_n \frac{\sigma^2}{p(\sigma)} \delta(\sigma - n\sigma_d)_I \quad (21a)$$

where:

$$k = (I/C)^{1/2}$$

$$D_n = e^{-nm_e^2} \quad \text{for unmodulated carrier interference} \quad (21b)$$

$$= e^{-2nm_e^2} \quad \text{for same type-modulated FDM-FM interference} \quad (21c)$$

$$m_e^2 = \left[C_0 + (C_2/\beta) + \frac{C_\mu}{3\beta^3} (\beta^2 + \beta + 1) \right] m_{e0}^2 \quad (21d)$$

$$m_{e0}^2 = m_1^2 \beta \quad (21e)$$

β : upper to lower frequency ratio in the wanted signal baseband

$$\sigma = f/f_{m_1} \quad (21f)$$

$$p(\sigma) = C_0 + C_2(\sigma)^2 + C_\mu(\sigma)^4 \quad (21g)$$

$$\delta(\sigma - \sigma_d)_I = 1 \quad \text{for } \sigma = \sigma_d \quad (21h)$$

$$= 0 \quad \text{for } \sigma \neq \sigma_d$$

The influence of tone interference tends to become substantial in cases where the frequency separation f between carriers of the wanted and interfering signals falls into the baseband or particular regions, such as the pilot, the frequency slot of detected noise, a possible super-baseband service channel and DAV subscriber. In this case, the design requirements with respect to interference should be determined in the light of the tone interference.

2. Signal spectra

2.1 Analogue telephony (FDM-FM) signal

The signal's normalized power spectral density centred on the carrier frequency is expressed as:

$$P(f) = e^{-a} \left[\delta(f) + \sum_{n=1}^{\infty} \frac{m^{2n}}{n!} S(f)^n * S(f) \right] \quad (22)^*$$

where:

$\delta(f)$: Dirac delta function
 $S(f)^n * S(f)$: convolution of the function $S(f)$ n times itself
 $S(f)$: normalized spectral density of the signal phase:

$$S(f) = \frac{f_m p(f/f_m)}{2f^2 (1 - \epsilon)} \quad (23)$$

where ϵ is the lower to upper frequency ratio in the wanted signal baseband.

* Although the series of formula (22) converges for all values of system parameters, it does not always provide the most appropriate algorithm for numerical computation, particularly in cases where the normalized r.m.s. multi-channel phase and/or frequency deviation (a and m respectively) are large.

The CCIR pre-emphasis characteristics are well approximated by the expression:

$$p(f/f_m) = 0.4 + 1.35 \left(\frac{f}{f_m} \right)^2 + 0.75 \left(\frac{f}{f_m} \right)^4, \quad \text{when } \varepsilon \leq \frac{f}{f_m} \leq 1 \quad (24)$$

Here:

$$a = R_s(0) - R_s(\infty) \approx \frac{m^2}{\varepsilon} (0.4 + 1.6 \varepsilon + 0.25 \varepsilon^2 + 0.25 \varepsilon^3) \approx \frac{m^2}{\varepsilon} (0.4 + 1.6 \varepsilon) \quad (25)$$

where:

$R_s(\tau)$: the autocorrelation function of $S(f)$.

The normalized power of the vestigial signal carrier is expressed as e^{-a} .

When $m > 1$:

$$\begin{aligned} P(f) &= \frac{1}{f_s \sqrt{2\pi}} e^{-\frac{f^2}{2f_s^2}} \left\{ 1 + \sum_{n=2}^{\infty} (-1)^n \frac{C_{2n}}{m^{2n} 2^n} H_{2n} \left(\frac{f}{f_s \sqrt{2}} \right) \right\} \approx \\ &\approx \frac{1}{f_s \sqrt{2\pi}} e^{-\frac{f^2}{2f_s^2}} \left\{ 1 + \frac{6.375 \cdot 10^{-2}}{m^2} H_4^* \left(\frac{f}{f_s \sqrt{2}} \right) - \frac{7.416 \cdot 10^{-3}}{m^4} H_6^* \left(\frac{f}{f_s \sqrt{2}} \right) + \right. \\ &\quad \left. + \left[\frac{2.37 \cdot 10^{-2}}{m^4} + \frac{7.16 \cdot 10^{-4}}{m^6} \right] H_8^* \left(\frac{f}{f_s \sqrt{2}} \right) - \left[\frac{9.929 \cdot 10^{-3}}{m^6} + \frac{5.854 \cdot 10^{-5}}{m^8} \right] H_{10}^* \left(\frac{f}{f_s \sqrt{2}} \right) \right\} \quad (26) \end{aligned}$$

where:

f_s : r.m.s. multi-channel signal frequency deviation

$H_{2n}^*(x) = (-1)^n \frac{n!}{(2n)!} H_{2n}(x)$: normalized Hermite polynomial.

Figures 2a to 2e contain spectral graphs plotted according to formulae (22) and (26) for modulation indices m adopted in typical radio-relay and communication-satellite systems.

The curves are approximate in the region f/f_m near 0 and 1. The exact values depend upon the particular value of ε . The exact curves for several values of ε are given in Figs. 2f to 2j for f/f_m near zero. (The inset curves in Figs. 2d to 2e are also accurate enough for f/f_m near zero if ε is equal to or greater than 0.02.)

For modulation indices greater than 1.1, the following empirical formula has been found to fit adequately the curves of $P(f)$ and is a good approximation of equation (26):

$$f_m \cdot P(f) = \frac{1}{m \sqrt{2\pi}} e^{-\frac{x^2}{2m^2(1 + 0.01337 x^2 \cdot m^{-1.367})}} \quad (26a)$$

where:

$$x = f/f_m.$$

This empirical formula is an adaptation of the Gaussian formula for large modulation indices.

FIGURE 2a
Normalized power spectral densities
for various modulation indices

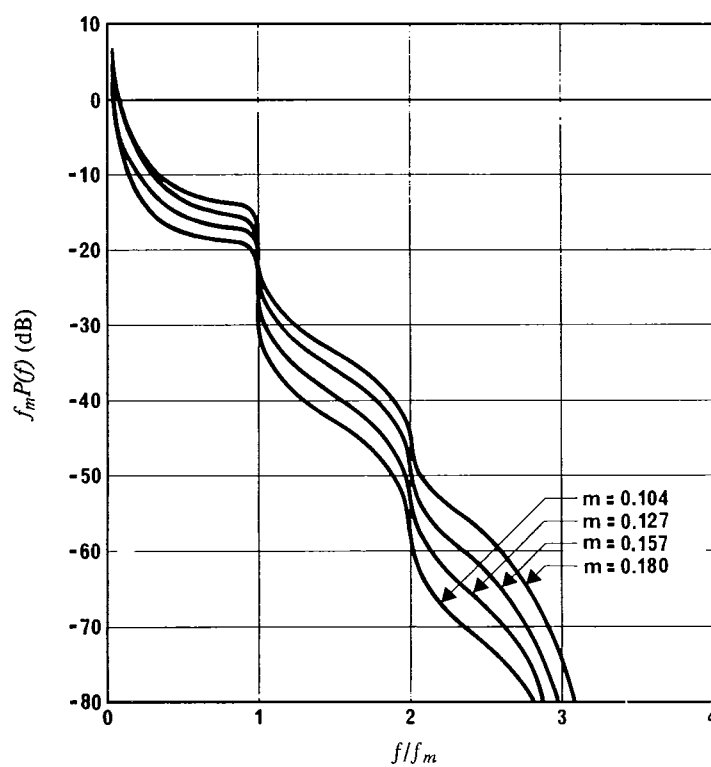


FIGURE 2b
Normalized power spectral densities
for various modulation indices

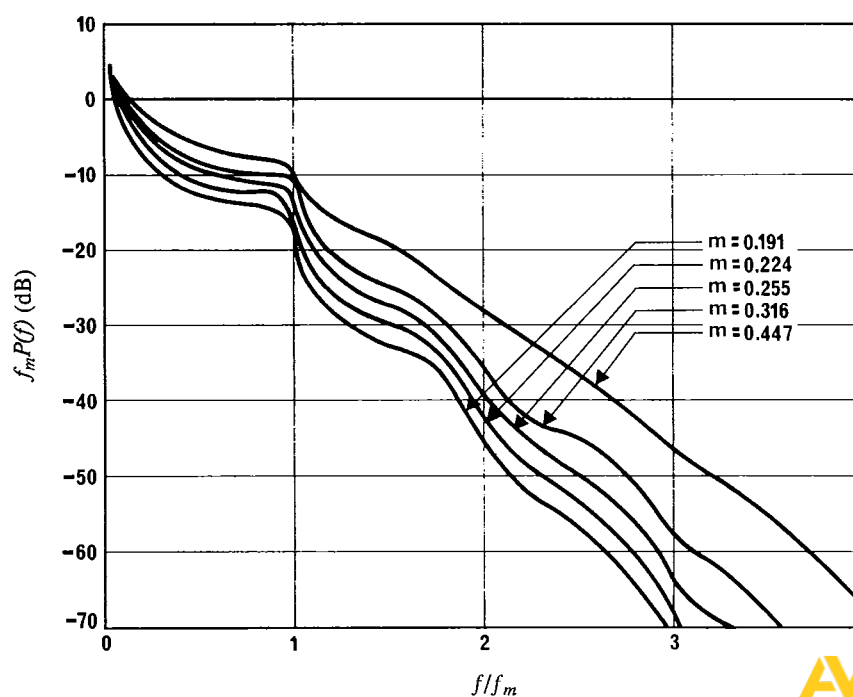


FIGURE 2c
Normalized power spectral densities
for various modulation indices

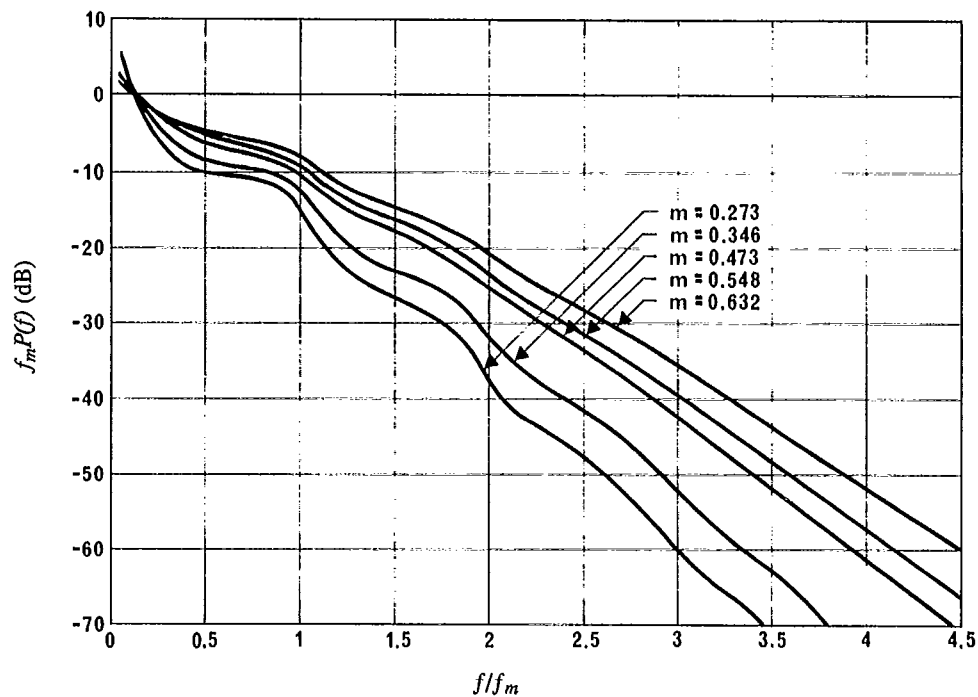


FIGURE 2d
Normalized power spectral densities
for various modulation indices

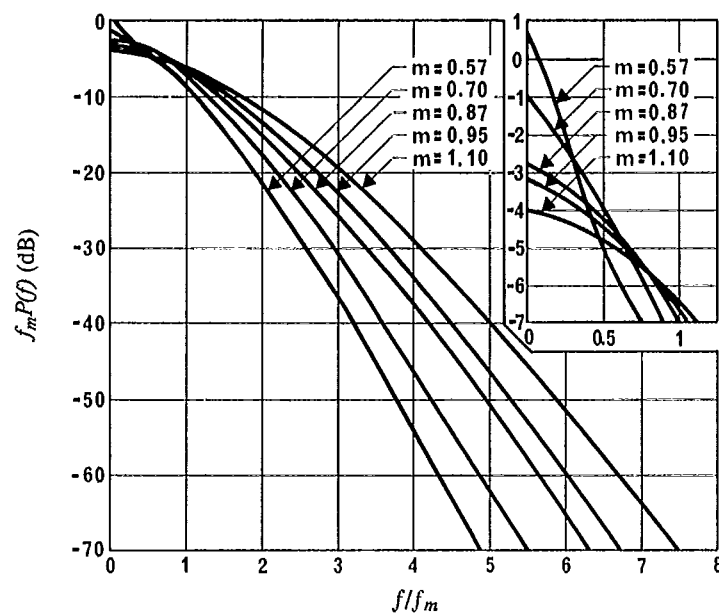


FIGURE 2e

Normalized power spectral densities
for various modulation indices

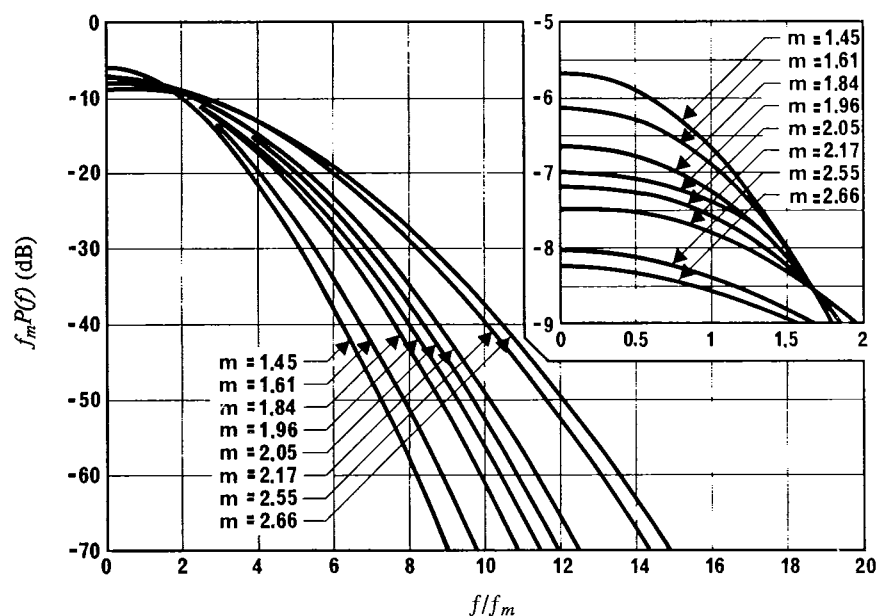
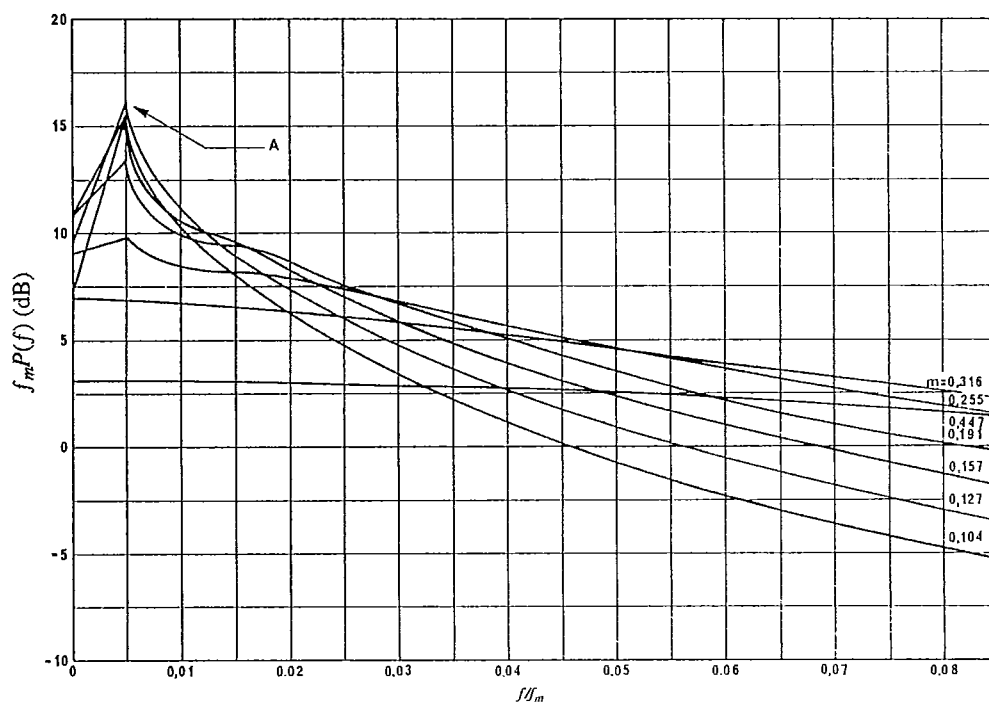


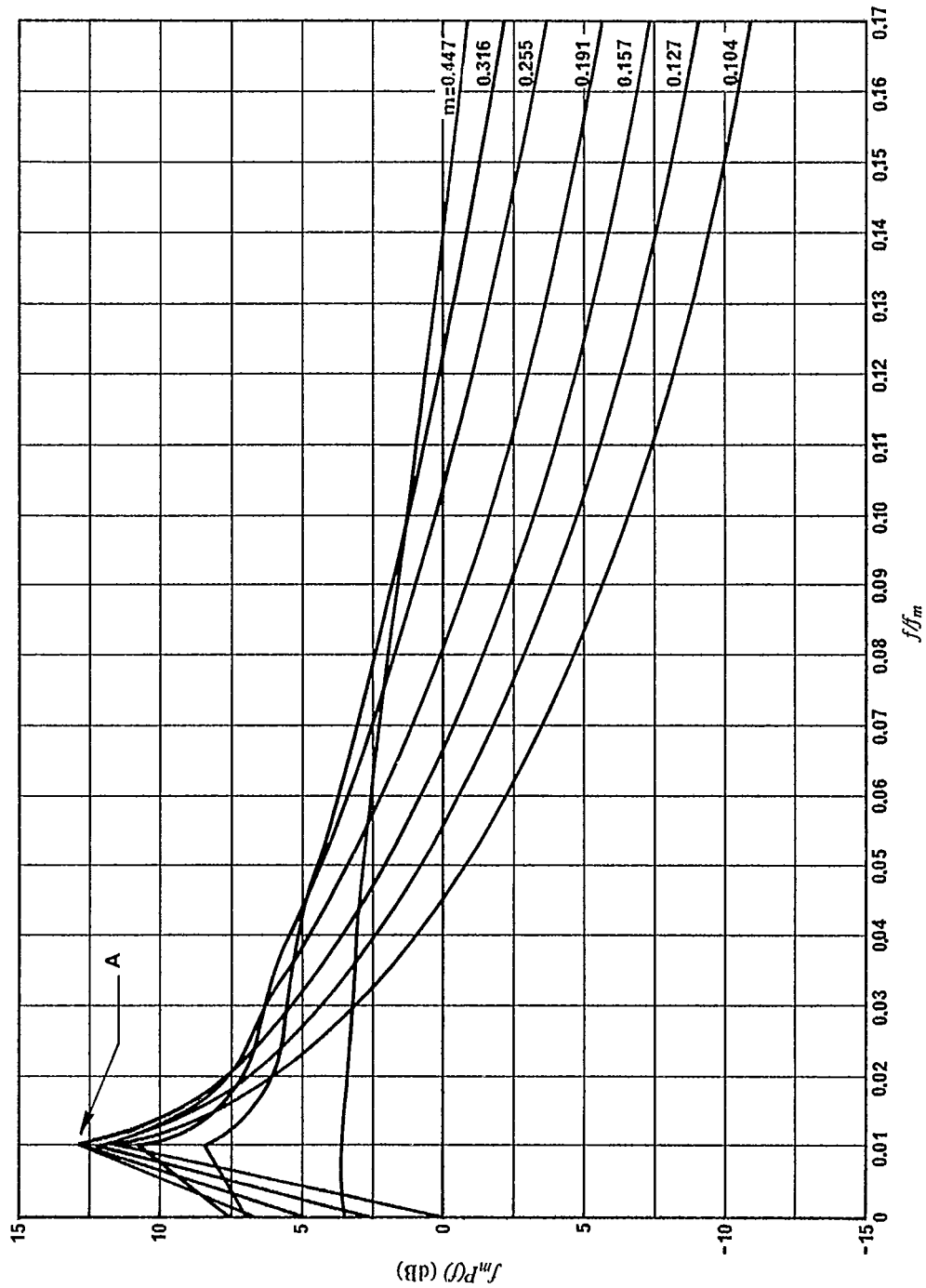
FIGURE 2f

Normalized power spectral densities for various modulation indices and for $\varepsilon = 0.005$



A: Peak values in dB are 15.9, 15.9, 15.2, 13.6, 9.8, 7.1, 3.2
for $m = 0.104$ to 0.447 respectively

FIGURE 2g
Normalized power spectral densities for various modulation indices and for $\epsilon = 0.01$



A: Peak values in dB are 11.6, 12.4, 12.8, 12.9, 10.9, 8.3, 3.5 for $m = 0.104$ to 0.447 respectively