REPORT 923-1

DESIGN OF FREQUENCY PLANS FOR SATELLITE TRANSMISSION OF SCPC CARRIERS USING NON-LINEAR TRANSPONDERS

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1. Introduction

In satellite communication systems, a number of SCPC carriers are transmitted via a single satellite transponder. For efficient use of satellite power, the transponder would be operated in the non-linear region, in which case intermodulation noise affects signal quality.

The intermodulation products falling into the frequency slots of occupied signal channels could be reduced by suitably positioning the channels within the available bandwidth. Babcock spacing [Babcock, 1953] is a typical example of this approach where the signal channels are completely free from third-order intermodulation noise. However, such an intermodulation-free frequency plan would not necessarily be desirable because of its inefficient use of available bandwidth, especially where a large number of channels have to be accommodated. For example, in order to accommodate 20 channels, it would be necessary to utilize a bandwidth more than 10 times the width of a plan using adjacent frequency slots [Hirata and Yasuda, 1976]. Hence, bandwidth-efficient frequency plans need to be developed, and one approach is to allow some intermodulation products to fall into the signal channels, but only to the extent that the degradation of signal quality can be acceptable.

A reasonable and effective approach to realize such an idea is to minimize the number of the third-order intermodulation products falling into the worst signal channel [Hirata, 1978]. The worst signal channel here means a specific signal channel into which the largest number of the third-order intermodulation products fall. This Report discusses the assignment of frequencies based on this approach, which is referred to hereafter as intermodulation-minimum frequency assignment.

2. Equal level SCPC carriers

2.1 *Relationship between assigned bandwidth and intermodulation products*

It is difficult to determine theoretically intermodulation minimum frequency plans. However, the attainable minimum number of intermodulation products falling into the worst affected signal channel can be estimated by the theoretically derived lower bound.

Figure 1 shows the theoretically derived lower bounds of the number of the $(f_1 + f_2 - f_3)$ type of the third-order intermodulation products falling into the worst signal channel as a function of the assigned bandwidth with a parameter of the number of signal channels to be accommodated. In this Figure, the number of intermodulation products, which is proportional to the intermodulation noise power, is normalized against the number produced in the worst signal channel in a plan using adjacent frequency slots. The result is then expressed in decibels. For convenience, the latter plan is referred to hereafter as minimum equal-spacing. The assigned bandwidth is also normalized by that required for the minimum equal-spacing plan. This Figure implies that the number of intermodulation products falling into the worst signal channel could be reduced to about one half compared to the case of minimum equal-spacing when the total frequency bandwidth occupied is 50% wider than that required for minimum equal-spacing.

2.2 *Intermodulation-minimum frequency plan*

Intermodulation-minimum frequency plans have been obtained for practical application by computer calculation. For a small number of signal channels, the optimum solution can be obtained by examining all possible combinations. Table I shows the results obtained where the number of signal channels K is 10.

For a large number of signal channels, the quasi-optimum solution, which may not be optimum but would be considered very close to optimum, can be obtained by an iterative approach [Okinaka *et al.*, 1982]. Table II shows the obtained results where K is 20 in IIa and 40 in IIb, respectively.

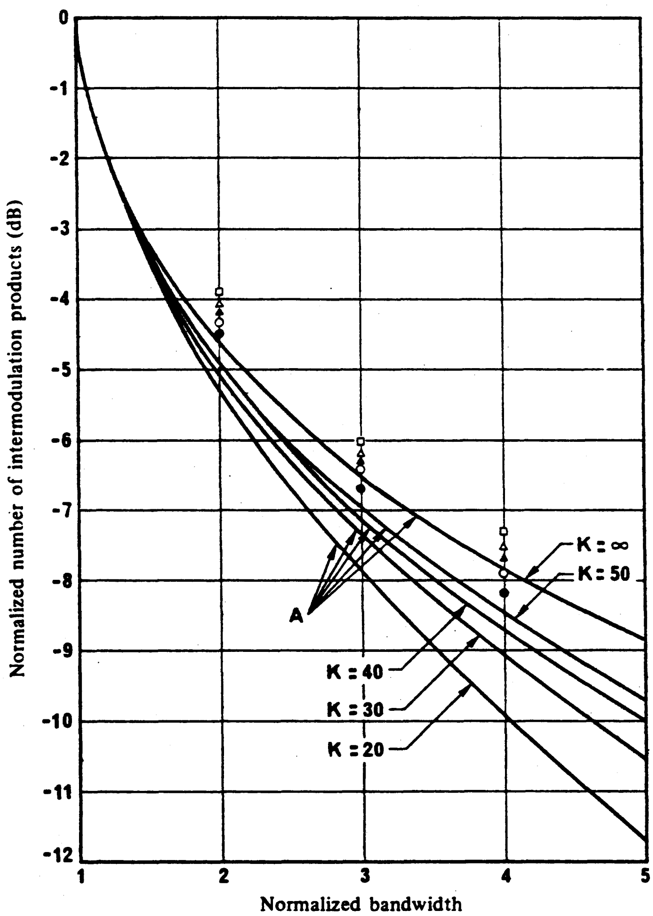

FIGURE 1 – *Relationship between the number of intermodulation products falling into the worst signal channel and the assigned bandwidth*

Obtained results:

● : K = 20

○ : K = 30

▲ : K = 40

△ : K = 50

□ : K = 100

A : lower bounds

K : number of signal channels

TABLE I — *Optimum intermodulation-minimum frequency plans (number of signal channels, K = 10)*

Number of frequency slots	Normalized bandwidth	Normalized number of IM products (dB)	Assigned frequency slots
11	1.1	−1.0	1, 2, 3, 4, 5, 7, 8, 9, 10, 11
12	1.2	−1.7	1, 2, 3, 4, 6, 7, 9, 10, 11, 12
13	1.3	−2.4	1, 2, 3, 4, 6, 7, 10, 11, 12, 13
14	1.4	−3.0	1, 2, 3, 4, 6, 7, 10, 12, 13, 14
15	1.5	−3.5	1, 2, 3, 4, 7, 8, 11, 13, 14, 15
16	1.6	−3.9	1, 2, 3, 4, 7, 10, 12, 14, 15, 16
17	1.7	−4.3	1, 2, 3, 4, 7, 10, 12, 14, 16, 17
18	1.8	−4.7	1, 2, 3, 5, 7, 10, 13, 16, 17, 18
19	1.9	−5.2	1, 2, 3, 5, 9, 12, 14, 17, 18, 19
20	2.0	−5.4	1, 2, 3, 6, 8, 12, 15, 18, 19, 20
21	2.1	−5.7	1, 2, 3, 5, 10, 14, 15, 18, 20, 21

The normalized number of intermodulation products shown in Tables I and II are plotted in Fig. 1. Comparing them with their lower bounds, it is observed that the number of intermodulation products falling into the worst signal channel in the intermodulation-minimum frequency plans can be estimated effectively by using the lower bound curve for $K = \infty$ shown in Fig. 1.

3. Multi-level SCPC carriers

In future satellite systems it may be desirable to operate with several standards of mobile earth stations having different G/T values. One possibility would be to transmit signals destined to the various mobile earth station standards with different satellite e.i.r.p. levels. Even within systems that operate with a single mobile earth station standard, different satellite carrier power levels may be used for different services.

However, accommodation of large numbers of carriers of mixed power levels in a single non-linear satellite transponder by placing the carriers in arbitrarily-selected channel assignments could easily lead to situations where intermodulation noise from certain relatively higher-power channels would render several relatively lower-power channels unusable.

A carefully developed frequency plan, resulting in a distribution of intermodulation noise among channels in such a way as to be proportional to the carrier power of the channel could prevent such a situation.

This section briefly describes several frequency plans for multi-level carriers.

3.1 *Mixed-level frequency plan alternatives*

One type of frequency plan capable of easily accommodating mixed level carriers assigns carriers to channels selected from a set of equally spaced channels using a Babcock spacing [Babcock, 1953: Edwards *et al.*, 1969]. Resultant assigned channels are totally free of third-order intermodulation noise and could consequently be used for carriers of any power level. However, Babcock plans are generally impractical, unless the number of required carrier assignments is small, due to the inefficient use such plans make of the available bandwidth.

TABLE II – *Quasi-optimum intermodulation-minimum frequency plans*

a) $K = 20$

Number of frequency slots	Normalized bandwidth	Normalized No. of IM products (dB)	Assigned frequency slots
40	2	−4.5	1, 2, 3, 5, 6, 7, 10, 16, 17, 19, 24, 26, 27, 32, 34, 36, 37, 38, 39, 40
60	3	−6.7	1, 2, 3, 6, 9, 12, 13, 19, 22, 27, 32, 41, 43, 47, 54, 55, 56, 58, 59, 60
80	4	−8.2	1, 2, 3, 4, 8, 11, 16, 28, 30, 41, 45, 52, 57, 61, 62, 70, 73, 76, 79, 80
100	5	−9.5	1, 2, 3, 5, 10, 17, 29, 31, 42, 45, 48, 65, 67, 80, 85, 89, 90, 96, 98, 100

b) $K = 40$

Number of frequency slots	Normalized bandwidth	Normalized No. of IM products (dB)	Assigned frequency slots
80	2	−4.2	1, 2, 3, 4, 5, 6, 7, 8, 10, 13, 16, 18, 22, 24, 25, 27, 28, 32, 35, 39, 43, 45, 46, 48, 52, 61, 62, 64, 65, 66, 70, 71, 72, 74, 75, 76, 77, 78, 79, 80
120	3	−6.3	1, 2, 3, 4, 5, 6, 7, 8, 12, 15, 17, 22, 31, 32, 34, 39, 45, 55, 57, 65, 67, 70, 77, 78, 82, 88, 91, 96, 97, 100, 105, 109, 111, 112, 113, 116, 117, 118, 119, 120
160	4	−7.6	1, 2, 3, 5, 7, 8, 10, 13, 20, 21, 25, 30, 31, 37, 40, 45, 56, 58, 66, 70, 71, 72, 79, 92, 104, 108, 115, 117, 126, 132, 136, 145, 148, 151, 152, 154, 156, 158, 159, 160
200	5	−8.7	1, 2, 3, 4, 6, 9, 10, 13, 20, 26, 32, 38, 45, 54, 58, 71, 75, 83, 85, 86, 104, 106, 117, 128, 132, 144, 146, 161, 164, 175, 176, 184, 185, 190, 192, 194, 195, 198, 199, 200

Improved efficiency at the expense of third-order intermodulation products falling in assigned channels can be achieved with "multiple Babcock" plans. For example, in the case of a two-level system, such plans are formed by placing two identical Babcock plans side by side in frequency, but separated by an amount approximately equal to the bandwidth of one of the identical plans, which are referred to hereafter as a "double Babcock" plan. The penalty paid for the increased carrier density is some third-order intermodulation products falling on assigned channels. It can be shown that, in an "n" carrier plan, precisely $(n/2)-1$ third-order products fall on each of the assigned channels when all carriers are active. Since such a plan still provides a substantial reduction in the number of third-order products within each assigned channel over that which could be obtained with uniform or random channel spacings, intermodulation performance may be sufficiently good to operate with mixed level carriers.

If required, performance of the "double Babcock" plan can be improved for any selected assigned channel by deleting its "twin" assigned channel in the opposite half of the plan. When this is done, the selected channel becomes totally free of third-order intermodulation products. Consequently these improved channels may be used for carriers either lower or higher in power than other channels of the plan. Although the bandwidth efficiency of this plan is better than that of a Babcock plan, it still utilizes bandwidth inefficiently and is useful only when small numbers of assignable channels are required.

More bandwidth-efficient plans can be achieved at the expense of higher levels of intermodulation noise falling into carrier channels. Two methods, "dedicated zone method" and "interleaving method", which achieve a significant improvement in bandwidth utilization efficiency while at the same time providing low intermodulation noise power in carrier channels, have been suggested [Okinaka *et al.*, 1982].

In the "dedicated zone method", a dedicated frequency band is provided within the available bandwidth for carriers of each power level, and the carriers are placed within the dedicated frequency band exclusively usable by them. If the dedicated frequency bands are properly placed within the whole bandwidth, the band for lower level carriers could be free from the intermodulation products caused by higher level carriers. If it is possible to separate the two dedicated bands by an unassigned band, the possibility of intermodulation products caused by higher level carriers falling into the dedicated frequency band for lower level carriers could be further reduced.

In the "interleaving method", the carrier of ith level is placed only on the (M_{j+i}) numbered frequency slots, where M represents the number of carrier levels, i an integer between one and M, j an integer between zero and $(B/M - 1)$, and B the number of the whole assignable frequency slots. In this method, the intermodulation products caused by three carriers of a certain power level necessarily fall into the frequency slots for carriers of the same power level, thus the intermodulation products caused by higher level carriers would not fall into the frequency slots for lower level carriers. In the case of a dual-level system, for example, the "interleaving method" leads to an "odd-even" plan, where high power carriers are placed on even-numbered slots and lower power carriers on odd-numbered slots.

In the case of a dual-level system, the third-order products created may be classified into one of 8 categories shown in Table III. The Table also shows the approximate relative powers of each product type assuming that the ratio of low power to high power carriers is equal to "r". The advantage gained with plans based on the "dedicated zone method" and the "interleaving method" is that the more powerful intermodulation products of category 1 do not fall in frequency slots where the lower power carriers are placed. In many cases, the "dedicated zone method" may provide larger reduction in the number of the intermodulation products falling into channels of the lower level carriers than the "interleaving method".

Actual frequency plans can be obtained by the following procedure. First, the positions of the lowest level carriers are determined within the frequency slots for them by using the iterative approach [Okinaka *et al.*, 1982]. Then, the positions of the next low level carriers are determined within the frequency slots for them by the iterative method, where the worst carrier-to-intermodulation noise power ratio (C/IM) among all carriers already placed is maximized. This procedure is repeated on a level-to-level basis until the positions of carriers of all levels are determined.

TABLE III – *Categories and relative powers of the third-order intermodulation products and channels into which the products may fall for a dual-level frequency plan*

Product category	Product type	Relative power	Channels into which the products may fall	
			Dedicated zone method	Interleaving method
1	$f_h+f_h-f_h$	1	For H carriers	For H carriers
2	$f_h+f_h-f_l$ $f_h+f_l-f_h$	r	For L carriers	For L carriers
3	$f_h+f_l-f_l$ $f_l+f_l-f_h$	r^2	For H and L carriers	For H carriers
4	$f_l+f_l-f_l$	r^3	For H and L carriers	For L carriers
5	$2f_h-f_h$	1/4	For H and L carriers	For H carriers
6	$2f_h-f_l$	$r/4$	Unused slots	For L carriers
7	$2f_l-f_h$	$r^2/4$	For H and L carriers	For H carriers
8	$2f_l-f_l$	$r^3/4$	For H and L carriers	For L carriers

Note 1. – f_h is used to indicate a frequency slot for a high-power carrier and f_l to indicate a frequency slot for a low-power carrier.

Note 2. – r is the ratio of low-power to high-power carrier powers.

Note 3. – H carrier is used to indicate a high-power carrier and L carrier to indicate a low-power carrier.

3.2 *Typical performance of a dual-level plan*

In order to compare two assignment methods for the multi-level systems, the C/IM improvement has been calculated for typical examples of two-level and three-level systems. The C/IM improvement means the amount of improvement in the worst C/IM compared with that for the frequency plan where the lowest-level carriers are equally spaced, and where the number of carriers are chosen so as to maintain the same output power in the satellite transponder. For the two-level system, it is assumed that ten carriers with a certain level and ten carriers with 10 dB higher level share a transponder. For the three-level system, it is assumed that ten carriers with a certain level (L), ten carriers with 7 dB higher level, and ten carriers with 10 dB higher level than L share a transponder. Furthermore, a normalized bandwidth of three is assumed for both cases.

Table IV summarizes the performance of the obtained frequency plans. The Table implies that the "dedicated zone method" could provide better C/IM in the lower power carrier channels than the "interleaving method".

4. Conclusions

It has been shown that the number of third-order intermodulation products falling into a channel slot can be substantially reduced by the use of a carrier assignment plan encompassing an assigned bandwidth greater than that for the minimum equal-spacing plan. It was also shown in Fig. 1 that the normalized number of intermodulation products depends on the number of carriers as well as the normalized assigned bandwidth, and that spectrum efficiency decreases with the number of carriers.

TABLE IV – *Comparison of performance of multi-level frequency plans based on the "dedicated zone method" and the "interleaving method"*

Number of carrier levels	Level of carriers (dB)	*C/IM* improvement (dB)	
		Dedicated zone method	Interleaving method
2	0	5.2	3.2
	10	5.2	5.3
3	0	3.2	2.8
	7	3.4	2.8
	10	6.2	5.1

Note. – *C/IM* improvement means the amount of improvement in the worst *C/IM* compared with that in the frequency plan where the lowest level carriers are equally spaced, and where the number of carriers is chosen so as to maintain the same output power in the satellite transponder.

In the case where carriers with multiple power levels must be transmitted, improved carrier-to-intermodulation noise power ratio performance for the lower power carriers can be achieved by the "dedicated zone method". With a proper selection of channel assignments using a procedure such as that suggested in this Report, substantial improvements in low power carrier *C/IM* can be achieved with a small sacrifice in high power carrier *C/IM.*

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