RECOMMENDED MINIMUM TELEMETRY FREQUENCY SPACING WITH CPFSK, CPM, SOQPSK, AND FQPSK SIGNALS

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ABSTRACT

This paper will present equations for calculating the minimum recommended frequency separation of two digital telemetry signals. The signals can be filtered continuous phase frequency shift keying (CPFSK), multi-h continuous phase modulation (CPM) [1], shaped offset quadrature phase shift keying-Telemetry Group (SOQPSK-TG, aka SOQPSK-A*) [2], or Feher's patented quadrature phase shift keying FQPSK-B (or FQPSK-JR [3]). The equations are based on measured data in an adjacent channel interference (ACI) environment for filtered CPFSK (aka PCM/FM), multi-h CPM (or CPM for short), SOQPSK-TG, FQPSK-JR, and FQPSK-B. This paper is an extension of my 2001 and 2002 International Telemetering Conference papers on this topic [4, 5]. The quantity measured was bit error probability (BEP) versus frequency separation at a given signal energy per bit to noise power spectral density ratio (E_b/N_o). The interferers were CPFSK, CPM, SOQPSK-TG or FQPSK-B (-JR) signals. The results presented in this paper will be for a desired signal bit rate of 1 to 20 Mb/s, one interferer 20 dB larger than the desired signal (a few tests included two interferers), and various center frequency spacings, interfering signals, receivers, and demodulators. The overall ACI test effort has collected data sets at several bit rates and with one and two interferers. The results will be useful to system designers and range operators as they attempt to maximize the number of Mb/s that can be simultaneously transmitted with minimal interference in the telemetry bands.

KEY WORDS

Adjacent channel interference, CPFSK, PCM/FM, FQPSK-B, FQPSK-JR, CPM, SOQPSK, aeronautical telemetry signal spacing

INTRODUCTION

Telemetry data rates are increasing and the amount of available telemetry spectrum has been decreasing. The combination of these two facts is driving efforts to increase the telemetry channel packing density. Methods to increase channel packing density include more spectrally efficient modulation methods (including FQPSK, SOQPSK, and multi-h CPM) and the use of "better" receiver filters. A test program was initiated to measure the effects of carrier-to-interference ratio (C/I) and channel spacing on BEP at various E_b/N_0 values. The test setup is shown in figure 1. The test setup shows three radio frequency (RF) sources however only two were used for most of the tests included in this paper. The data sources were independent, pseudo-random signals of length 2^{15}-1 or 2^{11}-1. The non-return-to-zero-level (NRZ-L) CPFSK, multi-h CPM, SOQPSK and FQPSK signals were generated with laboratory test equipment and amplified with a Class C non-linear amplifier. The RF signals were applied to a FastBit 2000A test set that controlled E_b/N_0 and C/I. The shaded items in figure 1 are part of the FastBit 2000A. The FastBit 2000A keeps the signal power fixed and varies the interference and noise power levels. The composite signal was connected to a telemetry receiver. The receiver's intermediate frequency (IF) signal was connected to a RF Networks model 2120 demodulator or a Nova Engineering multi-mode trellis demodulator model MMD22 when SOQPSK-TG or FQPSK-B (or –JR) was the desired signal and to a Nova Engineering model MMD22 when multi-h CPM was the desired signal. When CPFSK was the desired signal, either the receiver's internal demodulator and bit synchronizer or the Nova model MMD22 [6] were used.

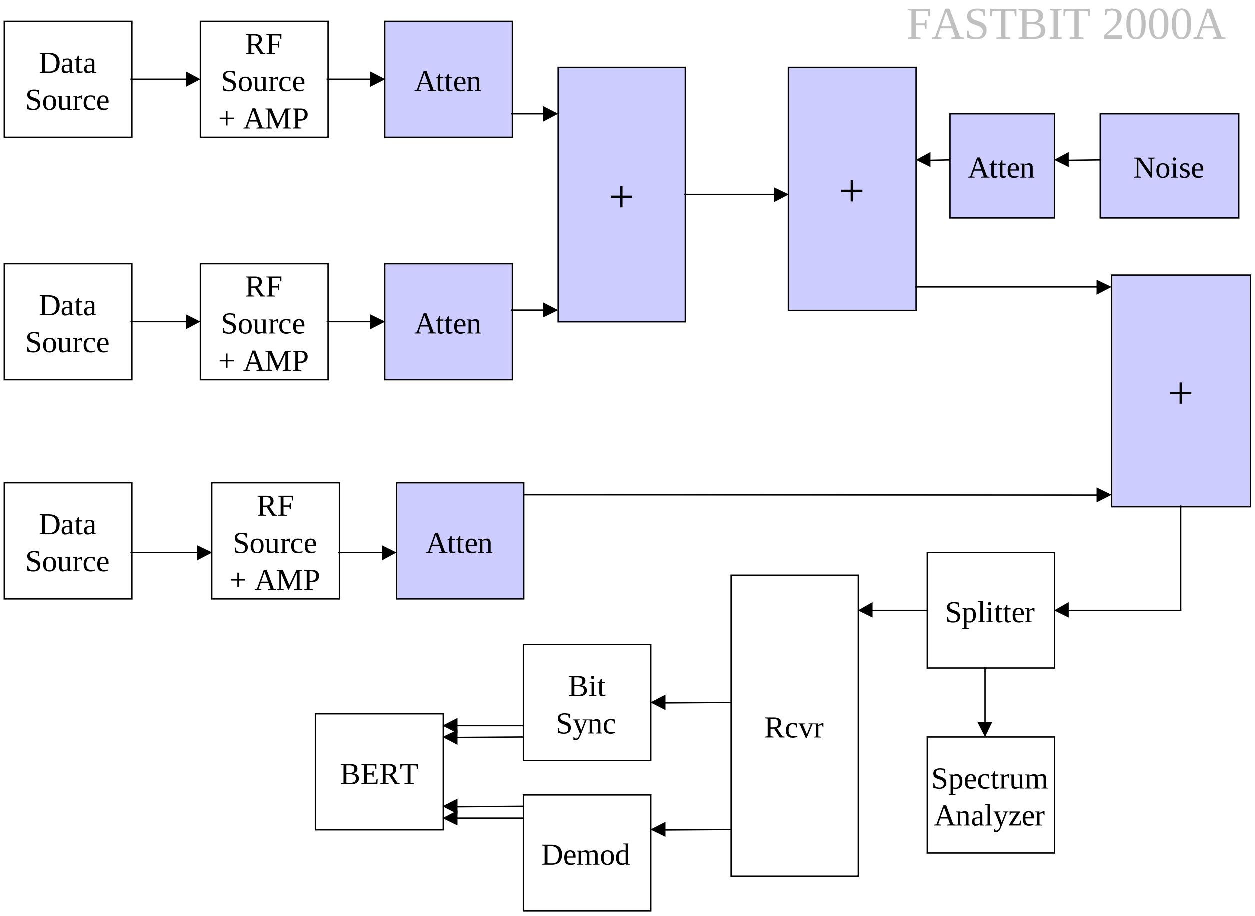

Figure 1. Test setup.

Sample spectra of the test signals are shown in figure 2. The CPFSK signals were premodulation filtered with a 6-pole linear phase filter with a bandwidth of 0.7 times the bit rate, had a peak deviation of 0.35 times the bit rate, and were generated with the appropriate signals from a Rohde&Schwartz AMIQ driving the I/Q inputs of the RF generator or with a filtered baseband signal driving the FM input. CPM and SOQPSK-TG signals were generated using a Rohde&Schwartz AMIQ driving the I/Q inputs of the RF generator. Mark Geoghegan of Nova Engineering supplied the above AMIQ files. FQPSK-JR (and –B) base band signals were generated using either a RF Networks base band processor board assembled into a chassis by Edwards AFB personnel or AMIQ files supplied by Robert Jefferies, Tybrin Corp., Edwards AFB. The RF sources were Agilent model E4433As. These RF signal generators have both frequency modulation (FM) and quadrature (I/Q) modulation capability. The FQPSK tests were conducted with I/Q modulator imbalances that cause spectral expansion typical of the near-worst case measured FQPSK transmitters (note where FQPSK-JR spectrum is wider than SOQPSK-TG below –45 dBc in figure 2; this spectral regrowth is caused by a combination of I/Q modulator errors and the effects of the non-linear amplifier).

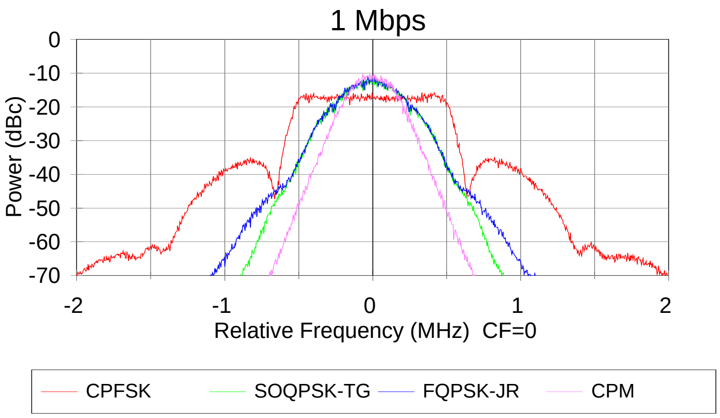

Figure 2. Signal spectra.

TEST RESULTS

BEP versus E_b/N_0 data were measured with various frequency spacings for a variety of desired and interfering bit rates, desired and interfering modulation methods, and various receivers and demodulators. Some of the test data will be presented in this paper but additional data will be contained in the 2004 edition of the Telemetry Applications Handbook (RCC Document 119-04).

Figure 3 presents BEP versus E_b/N_0 data with 5 Mb/s NRZ-L PCM/FM as both the desired signal and interfering signal with several values of spacing between the signals (the frequency spacing in MHz is shown in the legend). I found that the degradation increased fairly slowly as the spacing was decreased and when the degradation was greater than about 0.5 dB the degradation started to increase rapidly (note in figure 3 that the first few curves are close to the no interference (No I) curve but the last two start to move up and to the right rapidly). What is

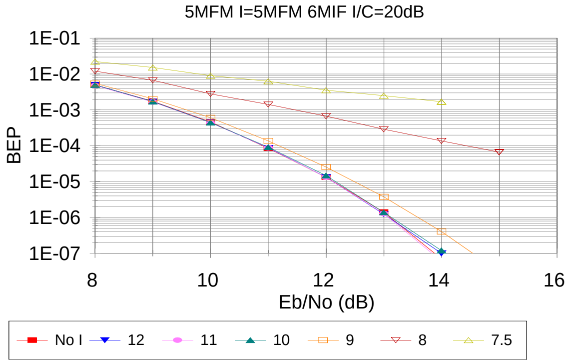

Figure 3. ACI effects with 5 Mbps PCM/FM.

happening is that the interfering power getting to the bit detector is starting to be a significant fraction of the noise power. The curves are similar for all of the combinations of modulation methods. The difference in E_b/N_0 values for a given BEP (a BEP of about 10^{-5} was used for this study) was estimated and used as the criteria for acceptable spacing.

Figures 4, 5 and 6 show measured BEPs for a fixed E_b/N_0 (the E_b/N_0 was fixed about 0.5 dB higher than the E_b/N_0 which gave a BEP of about 10^{-5}) for 5 Mb/s PCM/FM, SOQPSK-TG, and multi-h CPM with several interfering bit rates (interfering bit rate and modulation method are shown in the legend (5MDFM is 5 Mb/s PCM/FM)) and several frequency spacings. The solid horizontal line shows the BEP at 0.5 dB degradation. Figures 7 and 8 show the results of similar tests for 8 Mb/s SOQPSK-TG with intermediate frequency (IF) bandwidths of 8 and 16 MHz respectively. Note in figure 8 the curves for the 3 lowest rate interferers are all bunched together. The problem illustrated here is that the dynamic range of the demodulator is being exceeded because the receiver IF filter is not attenuating the interfering signal.

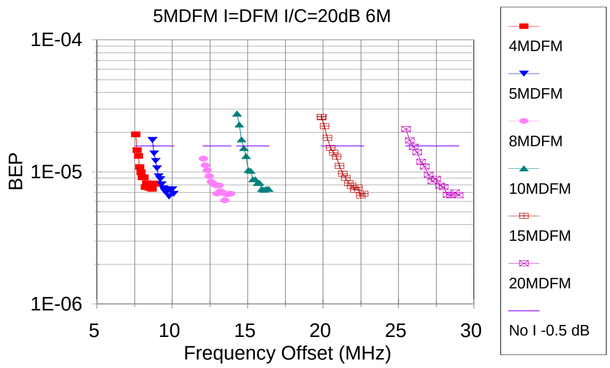

Figure 4. 5 Mbps PCM/FM with various interferers**.**

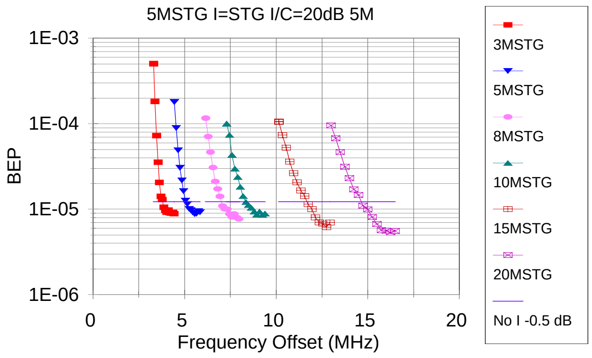

Figure 5. 5 Mbps SOQPSK-TG.

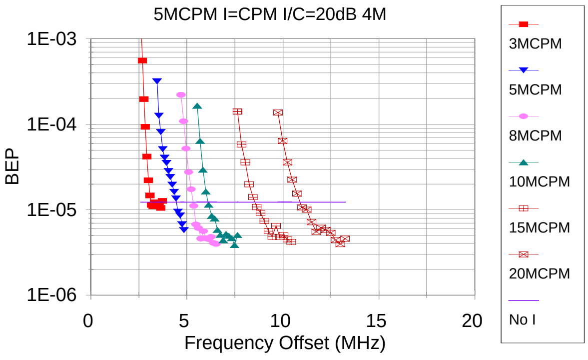

Figure 6. 5 Mbps multi-h CPM.

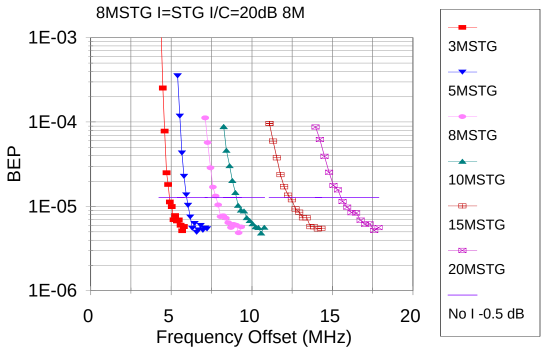

Figure 7. 8 Mbps SOQPSK-TG with 8 MHz IF BW.

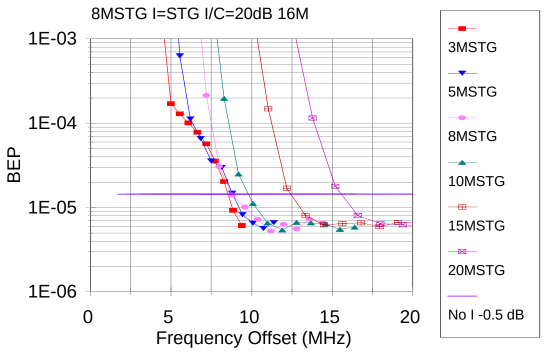

Figure 8. 8 Mbps SOQPSK-TG with 16 MHz IF BW**.**

Figures 9 and 10 show the results of tests where the C/I ratio was varied from –8 dB to –26 dB. These figures show that with a C/I ratio of –8 or –11 dB the differences between the performance with the two IF filters is small whereas with C/I ratios of –20, -23, and –26 dB the differences are fairly large. One of the main functions of the IF filter is to control the amount of interference power, which minimizes the instantaneous dynamic range at the input to the demodulator.

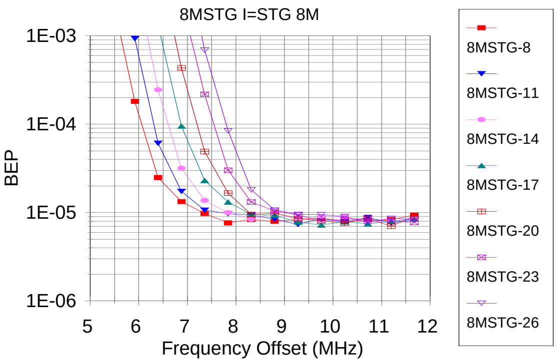

Figure 9. 8 Mbps SOQPSK-TG with 8 MHz IF BW and various C/I ratios.

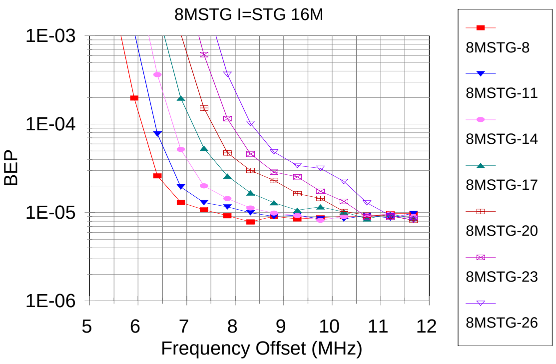

Figure 10. 8 Mbps SOQPSK-TG with 16 MHz IF BW and various C/I ratios.

Figures 11 and 12 show the results with the desired signal being 1 and 20 Mb/s PCM/FM and the interfering signal being 15 Mb/s PCM/FM. The receiver in this case had digitally generated IF filters. The minimum required separation is about 18 MHz in figure 11 and 31 MHz in figure 12. Since the interfering signal is the same, the difference is a function of the desired signal and the receiver/demodulator. For this case, the minimum required frequency spacing can be approximated by 0.7*S + 1.2*I where S is the bit rate of the desired signal and I is the bit rate of the interferer.

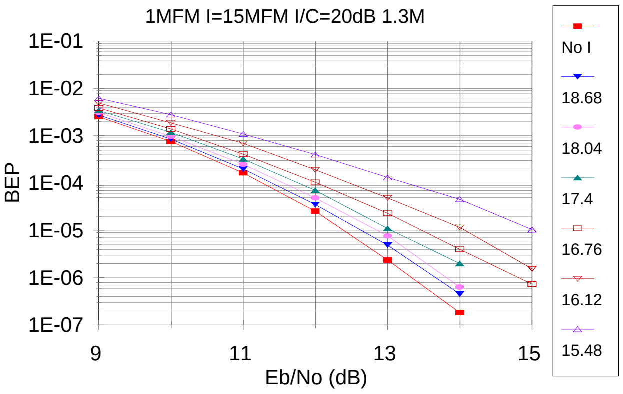

Figure 11. 1 Mbps PCM/FM with I=15 Mbps PCM/FM.

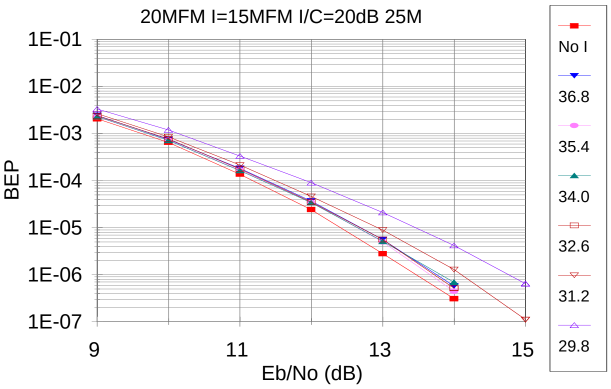

Figure 12. 20 Mbps PCM/FM with I=15 Mbps PCM/FM.

Figure 13 shows the co-channel interference performance of the various modulation methods with both desired signal and interferer set to 5 Mb/s (the first group of letters indicates the desired signal and the second the interferer, that is, FM-JR indicates the desired signal is PCM/FM and the interfering signal is FQPSK-JR). This figure shows that PCM/FM is the most resistant to co-channel interference and multi-h CPM is the least resistant.

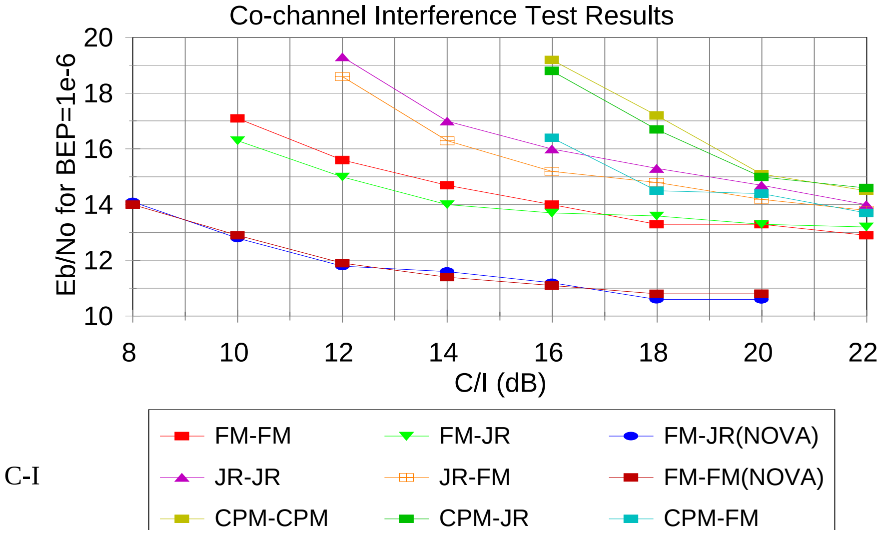

Figure 13. Co-channel interference test results.

Figure 14 shows the measured spacings for 0.5 dB degradation with 5 Mb/s SOQPSK-TG as the desired signal and various interfering signals. Note that the points for each interferer essentially form a straight line with the slope being different for each type of interference. This discovery greatly simplifies the expressions for required frequency spacing. One exception to this “rule” occurs when one of the adjacent signals is a high bit rate and the other is a low bit rate. In that case the required minimum spacing is a factor of the –6 dB IF bandwidth for PCM/FM with lumped constant (LC) receiver filters. This case is illustrated in figure 15. Note the flattening out of the 5M-LC curve with interfering bit rates below 5 Mb/s.

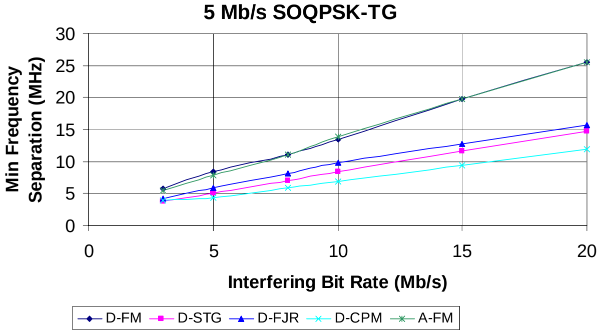

Figure 14. Minimum frequency separation.

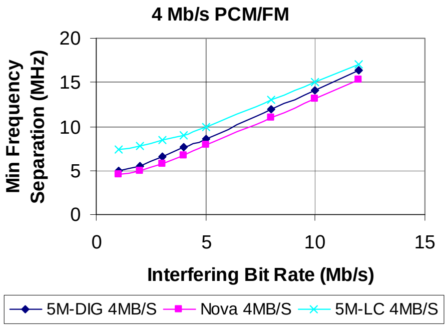

Figure 15. Minimum frequency separation for 4 Mb/s PCM/FM.

The minimum required frequency separations can be calculated using the formula:

$$\mathbf{DF = A*S + B*I}$$

Where:

DF is the minimum required frequency separation in MHz
S is the bit rate of the desired signal in Mb/s
I is the bit rate of the interfering signal in Mb/s
A is determined by the desired signal type and receiving equipment (see table 1 below)
B is determined by the interfering signal type (see table 1 below)

Table 1. Coefficients for frequency separation calculation.

Modulation Type	A	B
NRZ PCM/FM	**1.0*** for receivers with RLC final IF filters **0.7** for receivers with SAW or digital IF filters **0.5** with Nova multi-symbol detectors (or equivalent devices)	**1.2**
FQPSK-B, FQPSK-JR, SOQPSK-TG	**0.45**	**0.7**** FQPSK-B or –JR **0.65** SOQPSK-TG
Multi-h CPM	**0.35**	**0.5**

*The minimum frequency separation for typical receivers with RLC final IF filters and NRZ-L PCM/FM signals is the larger of 1.5 times the actual IF –3 dB bandwidth and the value calculated using the equation above.

**The value of B for FQPSK signals is a function of the modulator errors and is equal to 0.65 with no significant modulator errors.

The minimum spacing needs to be calculated for signal 1 as the desired signal and signal 2 as the interferer and vice versa. It is interesting to note that the values for B match the normalized –50 dBc points for the four modulation methods shown in figure 2 quite closely. It isn't surprising that the required frequency spacing from the interferer is directly related to the power spectrum of the interfering signal. The values for A are a function of the effective detection filter bandwidths and the co-channel interference resistance of the modulation method and detector. The values for A and B are slightly conservative for most cases and assume that the receiver being used does not have spurious responses that cause additional interference.

Main assumptions:
The NRZ PCM/FM signals are assumed to be premodulation filtered with a multi-pole filter with -3 dB point of 0.7 times the bit rate and the peak deviation is assumed to be approximately 0.35 times the bit rate.

The receiver IF filter is assumed to be no wider than 1.5 times the bit rate and provides at least 6 dB of attenuation of the interfering signal.
The interfering signal is assumed to be no more than 20 dB stronger than the desired signal.
The receiver is assumed to be operating in linear mode; no significant intermodulation products or spurious responses are present.

Examples:

5 Mb/s PCM/FM and 6 Mb/s PCM/FM using Microdyne 1200MRC receivers with 6 MHz IF bandwidths (these receivers have RLC IF filters)

1.0*5 + 1.2*6 = 12.2 MHz   1.0*6 + 1.2*5 = 12 MHz   1.5*6= 9.0 MHz; the largest value is 12.2 MHz and the frequencies are assigned in 1 MHz steps so the minimum spacing is 13 MHz

5 Mb/s PCM/FM and 6 Mb/s PCM/FM using Microdyne 1200MRC receivers with 10 MHz IF bandwidths (these receivers have RLC IF filters)

1.0*5 + 1.2*6 = 12.2 MHz   1.0*6 + 1.2*5 = 12 MHz   1.5*10= 15.0 MHz; the largest value is 15.0 MHz and the frequencies are assigned in 1 MHz steps so the minimum spacing is 15 MHz

5 Mb/s PCM/FM and 6 Mb/s PCM/FM using Microdyne 1200MRC receivers with 6 MHz IF bandwidths and Nova demodulators

0.5*5 + 1.2*6 = 9.7 MHz   0.5*6 + 1.2*5 = 9 MHz; the largest value is 9.7 MHz and the frequencies are assigned in 1 MHz steps so the minimum spacing is 10 MHz

5 Mb/s PCM/FM and 6 Mb/s FQPSK-B using Microdyne 1200MRC receivers with 6 MHz IF bandwidths (these receivers have RLC IF filters)

1.0*5 + 0.7*6 = 9.2 MHz   0.45*6 + 1.2*5 = 8.7 MHz   1.5*6= 9.0 MHz; the largest value is 9.2 MHz and the frequencies are assigned in 1 MHz steps so the minimum spacing is 10 MHz

5 Mb/s PCM/FM and 6 Mb/s FQPSK-B using Microdyne RCB2000 receivers with 6 MHz IF bandwidths (these receivers have SAW/digital IF filters)

0.7*5 + 0.7*6 = 7.7 MHz   0.45*6 + 1.2*5 = 8.7 MHz; the largest value is 8.7 MHz and the frequencies are assigned in 1 MHz steps so the minimum spacing is 9 MHz

5 Mb/s SOQPSK-TG and 6 Mb/s SOQPSK-TG using Microdyne 1200MRC receivers with 6 MHz IF bandwidths (these receivers have RLC IF filters)

0.45*5 + 0.65*6 = 6.15 MHz 0.45*6 + 0.65*5 = 5.95 MHz; the largest value is 6.15 MHz so the minimum spacing is 7 MHz

SUMMARY

The minimum required frequency separation can be calculated using a fairly simple linear equation. The coefficients for this equation are contained in table 1. The most important factors in determining the required minimum separation are the power spectral density of the interfering signal, the C/I ratio, the receiver filter bandwidth and roll-off rate, and the demodulator characteristics. Receiver spurious responses will cause problems that may cause degradation at spacings wider than the minimum required spacing. Having a receiver that does not have spurious responses is very important if one wants to minimize interference effects. Some receivers don't have spurious responses with low input levels but do have spurious responses with larger input levels therefore the gain before the receiver should not be larger than required.

ACKNOWLEDGEMENT

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