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CCSDS - SFCG EFFICIENT MODULATION METHODS STUDY

A COMPARISON OF MODULATION SCHEMES

PHASE 1: BANDWIDTH UTILIZATION

(Response to SFCG Action Item 12/32)

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CCSDS RF AND MODULATION STUDY

A COMPARISON OF MODULATION SCHEMES

1.0 INTRODUCTION

At its 12th annual meeting the Space Frequency Coordination Group, SFCG-12, held during November 1992 in Australia, the SFCG requested the CCSDS RF and Modulation Subpanel to study and compare various modulation schemes (SFCG Action Item 12-32). Further explanation and clarification of this request was provided by the SFCG's representative to Subpanel lE during the CCSDS RF and Modulation meeting at JPL from 8-12 February 1993. Several attributes such as bandwidth needed, power efficiency, spurious emissions, and interference susceptibility were the benchmarks suggested for comparing the several modulation schemes.

As the presently allocated frequency bands become more congested, it is imperative that the most bandwidth-efficient communication methods be utilized. Additionally, space agencies are under constant pressure to reduce costs. Budget constraints result in simpler spacecraft carrying less communications capability as well as reduced staffing at the earth stations used to capture the data. Therefore, the power-efficiency of each modulation scheme becomes an important discriminator in the evaluation process.

The following paper explores both those modulation schemes, which have been traditionally employed by space agencies together with newer techniques promising significantly improved communications channel efficiencies. This paper represents an interim report to the SFCG since modulation schemes such as QPSK, OQPSK, and MSK have not yet been studied, Supporting analysis for the information contained in this paper was by Tien M. Nguyen and can be found in References 1, 2, 3, and 5.

2.0 BANDWIDTH MEASUREMENT

2.1 Traditional Modulation Methods

Traditionally, space agencies have employed subcarriers for both telecommand and telemetry data transmissions. Subcarriers provided a simple method for separating different types of data as well as ensuring no overlap between the modulated data's frequency spectra and the RF carrier. It was not uncommon for early spacecraft to have two or more subcarriers.

Subcarrier modulation suffers the disadvantages of greater spacecraft complexity, additional losses in the modulation/ demodulation process, and a large occupied bandwidth. An effort was made to mitigate the latter effect by specifying that Category A missions utilize sinewave subcarriers while Category B missions should use squarewave subcarriers (CCSDS Recommendation 401 (2.4.5) B-l). Although requiring more bandwidth, square wave subcarriers were found to be acceptable for deep space missions because the weaker signals from such spacecraft, together with the separately allocated frequency bands, ensured that spacecraft transmissions would not interfere with one another. They offered the advantage of being less susceptible to in-band interference.

In the 1960s and 1970s, when data rates were low and only 2 or 3 channels required, the added complexity and spectrum utilization required when using subcarriers could be tolerated. Since then, missions have become more complex, technology has matured, and the radio frequency spectrum has become more congested. Greater data rates require higher frequency subcarriers, which expand the occupied bandwidth increasing the likelihood of overlapping downlinks from different spacecraft, which could interfere with one another.

Fortunately, new modulation techniques and improved data formatting can significantly reduce the amount of bandwidth needed to transmit information. Reference 4 describes a Packet Telemetry data format recommended by the Consultative Committee for Space Data Systems (CCSDS). These formats include a Transfer Frame into which Data Packets are placed. Three bits in the header of each Transfer Frame can be set by the user to indicate the type of data in that frame. Thus, the CCSDS *Packet Telemetry* system can provide up to eight separate and independent virtual channels.

The eight virtual channels are equivalent to eight separate, but simultaneous, data streams from the spacecraft. But, rather than employing eight subcarriers, these Transfer Frames (channels) are transmitted consecutively in a single data stream. By combining the CCSDS *Packet Telemetry* format with one of the direct modulation schemes discussed in this paper, and applying some judicious spectrum shaping, it is now possible to transmit messages at a high rate while using a comparatively small bandwidth. Before describing these alternative modulation systems, a reference for bandwidth measurement must be established.

2.2 Occupied Bandwidth

Several years ago the International Telecommunications Union (ITU) established criteria for quantifying the bandwidth used by a telecommunications system. Termed *Occupied Bandwidth*, RR-147, of the ITU's *Radio Regulations* defined the term as:

> *Occupied Bandwidth: The width of a frequency band such that, below the lower and above the upper frequency limits, the mean power emitted are each equal to a specified percentage $b/2$ of the total mean power of a given emission.*
>
> *Unless otherwise specified by the CCIR for the appropriate class of emission, the value of $b/2$ should be taken as 0.5%.*

Under the ITU definition, the *Occupied Bandwidth* is that span of frequencies which contains 99% of the emitted power. Where digital communications are concerned, *Occupied Bandwidths* of unfiltered signals tend to be very large. Some people believe that *Occupied Bandwidth* is not a useful concept for digital communications systems absent some degree of filtering.

The ITU *Radio Regulations* also contain an alternative definition called *Necessary Bandwidth.* RR-146 defines *Necessary Bandwidth* as:

> *Necessary Bandwidth: For a given class of emission, the width of the frequency band, which is just sufficient, to ensure the transmission of information at the rate and with the quality required under the specified conditions.*

Here, the problem is one of uncertainty. To a large extent "quality" is a subjective concept. Using *Necessary Bandwidth* definition is difficult without a specific standard. Moreover, no attention is paid to power efficiency, which would satisfy the requirements of both space and terrestrial communications systems. Generally, *Necessary Bandwidth* is not deemed to be a useful measure for space communications systems.

2.3 Required Bandwidth

Given the problems with both the *Occupied Bandwidth* and the *Necessary Bandwidth* notions, this paper proposes a new measure called *Required Bandwidth*. For the most part, the definition of *Required Bandwidth* is the same as that for *Occupied Bandwidth*. The principal difference is that a more realistic value for the percentage of power is selected. The proposed definition is:

> *Required Bandwidth: For a specific type of modulation, the width of the frequency band such that, below the lower and above the upper frequency limits, the mean power emitted are each equal to 2.5 percent of the total unfiltered, ideally modulated digital data spectrum, using the same modulation scheme.*

Note that this definition is not referenced to 99% of the power in the transmitted spectrum, as is the one for *Occupied Bandwidth*. That is because spectrum control is inherent in the concept of *Required Bandwidth*. In simple terms, *Required Bandwidth* is that bandwidth needed to complete a communication *with an acceptable amount of power loss*. For example, a 5% decrease in power corresponds to -0.2 dB. Such a reduction should be acceptable to most space missions. Yet, the bandwidth required to send identical messages over two channels, one using the *Occupied Bandwidth definition and the other employing the new Required Bandwidth definition, will be several times less in the latter channel when compared to the former*. As will be demonstrated in the remainder of this paper, accepting a small loss in the system's performance dramatically reduces the amount of bandwidth needed to complete the communication.

It is assumed that some spectrum shaping will be employed at an appropriate location in the information transmission system so that *only the Required Bandwidth is transmitted from the spacecraft*. Figure 2-1 is a simplified block diagram of a spacecraft Radio Frequency Subsystem (RFS). Note that spectrum shaping can be located in the ranging channel, at the input to the modulator, and at the output of the power amplifier. Spectrum shaping is found on most current spacecraft. All of the spectrum shaping devices shown in Figure 2-1 may not be required. The actual number and their locations will depend upon the specific RFS design and the linearity of the multiplier and the power amplifier. Obviously, it is desirable to avoid spectrum shaping at the output of the power amplifier because of the RF power loss and increased weight. If the spectrum shaping is done at an earlier point, then the losses resulting from spectrum shaping at the transmitter's output can be largely avoided.

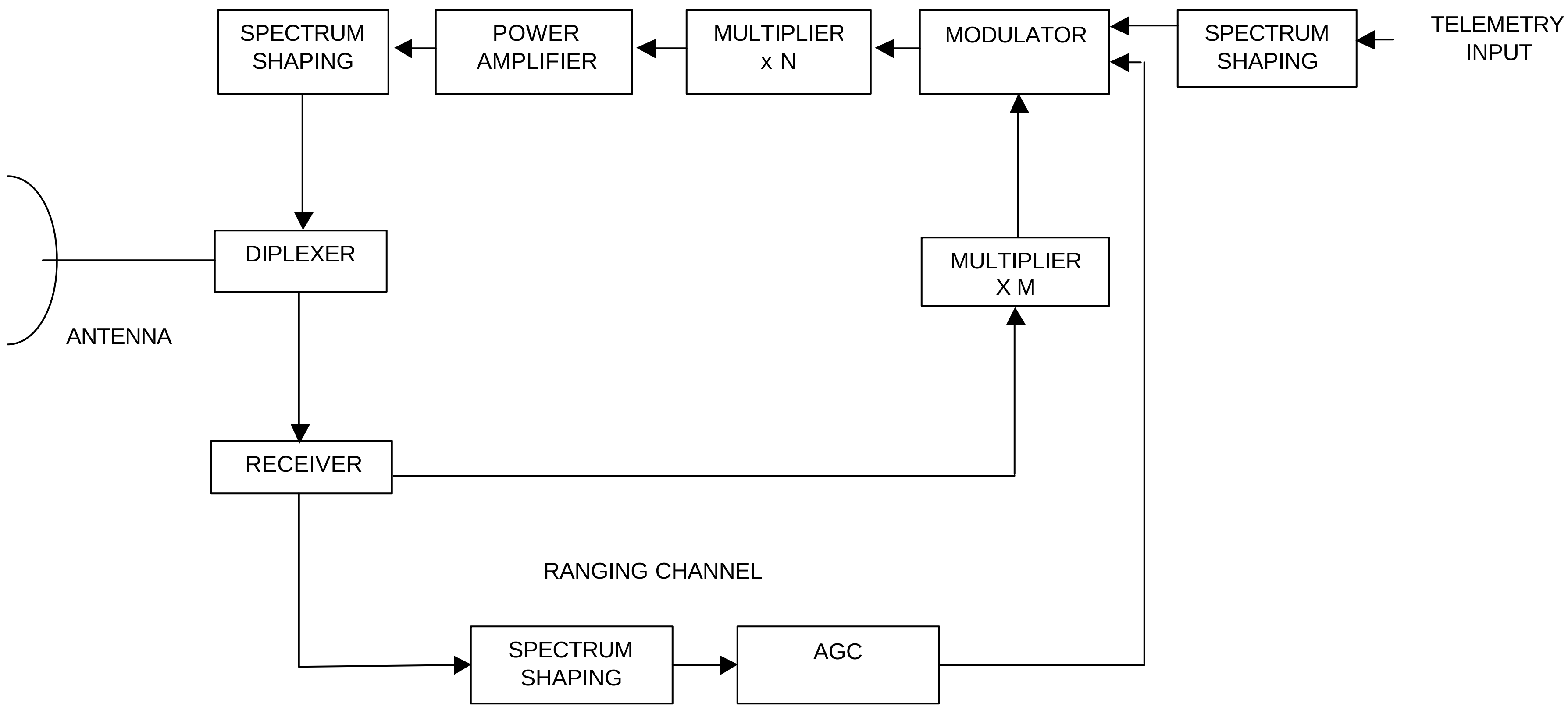

Figure 2-1. Simplified Block Diagram of Spacecraft Radio Frequency Subsystem

Coherent turnaround and one-way ranging signals present unique problems in *Required Bandwidth* systems. To achieve the desired measurement accuracy, ranging tones sometimes have frequency components, and hence *Required Bandwidths*, which are larger than those needed for telemetry and telecommand operations. Since many space missions need all of these services, the RFS depicted in Figure 2-1 must accommodate the separate spectral requirements imposed by the different services. Clearly, the mechanization of the flight radio system may depend upon a mission's specific requirements.

Fortunately, the system depicted in Figure 2-1 should permit the flexibility to meet the needs of all services. Moreover, even if the *Necessary Bandwidth* increases during ranging operations, these sessions are usually concluded quickly so that the increased bandwidth requirement is of short duration.

3.0 COMPARISON OF MODULATION SCHEMES

Modulation schemes listed in Table 3-1 were investigated in Reference 1 and are compared in this paper. Because this is an interim report, QPSK, OQPSK, and MSK (including GMSK), have not been studied yet and will be included in the final report. Modulation methods listed below are shown in the order of increasing bandwidth efficiency (diminishing *Required Bandwidth*).

TABLE 3-1: INVESIGATED MODULATION SCHEMES

Modulation Type	Description
PCM/PSK/PM squarewave	NRZ data is PSK modulated on a squarewave subcarrier, which is then phase modulated on a residual RF carrier.
PCM/PSK/PM sinewave	NRZ data is PSK modulated on a sinewave subcarrier, which is then phase modulated on a residual RF carrier.
PCM/PM/Bi-ϕ	Data is Bi-Phase (Manchester) modulated directly on a residual RF carrier.
PCM/PM/NRZ	NRZ data is phase modulated directly on a residual RF carrier.
BPSK/Bi-ϕ	Data is Bi-Phase (Manchester) modulated directly on an RF carrier fully suppressing it.
BPSK/NRZ	NRZ data is modulated directly on an RF carrier fully suppressing it.

To compare the *Required Bandwidths* for the several modulation schemes, power transfer efficiencies of 90% and 95% are used. As noted above, these correspond to power losses of 0.45 dB and 0.2 dB respectively. For each modulation type the bandwidth needed to convey 90% and 95% of the modulated signal will be computed. Bandwidths will be normalized to the data Symbol Rate, Rs, so that the various types can be compared. Additionally, an RF carrier modulation index of 1.2 radians, a value typical for primary telemetry channels having reasonable data rates, was used for evaluating all modulation schemes.

Figure 3-1 shows the frequency spectrum of each of the several modulation schemes shown in Table 3-1. One need look no further than this figure to see that there is a very large disparity in the bandwidths used by the several schemes.

A COMPARISON OF MODULATION SCHEMES

3.1 Subcarrier Modulation Schemes

Subcarriers were routinely used for telemetry channels. Not only did they facilitate separation of different data types, but also they served to separate the data's transmitted spectrum from the RF carrier. Spectral separation was particularly important in the early days of the space program when data rates were low and the data sidebands were frequently indistinguishable from the carrier.

In this analysis, both sinewave and squarewave subcarriers will be examined to determine their effect upon the *Required Bandwidth.*

3.1.1 Squarewave Subcarriers

CCSDS Recommendation 401 (2.4.5) B-1 states that Category B missions should employ squarewave subcarriers. Although requiring a larger bandwidth than sinewave subcarrier modulation schemes, use of squarewave subcarriers does provide slightly better performance at high modulation indices than do sinewave subcarrier systems. This is so because, if the receiver's bandwidth is sufficient, high order harmonics are recoverable whereas the high order Bessel functions, present with sinewave subcarriers at high modulation indices, are not. Figure 3-1 (a) shows the frequency spectrum of a system employing a single squarewave subcarrier. Limited space restricted the ability to show the full spectrum. Odd harmonics of the subcarrier's frequency, each with data sidebands, will be present with diminishing amplitude as the order increases.

Figure 3-2 shows the spectrum bandwidth needed for data systems employing squarewave subcarriers. All plots in this paper normalize the spectrum bandwidth to the data Symbol Rate[1], Rs (e.g., BW/Rs). Bandwidth is also dependent upon the ratio between the subcarrier's frequency and the symbol rate, as well as the RF carrier's modulation index. The reason for the former should be obvious while the latter is because, at lower modulation indices, a greater percentage of the transmitted power will be found in the carrier's comparatively narrow frequency band.

Three values for Subcarrier Frequency/Symbol Rate (n) corresponding to 3, 9, and 15 were evaluated. While these represent the minimum and maximum ratios generally used, some missions have been known to fly ratios as high as 1,000. A brief glance at Figure 3-2 will clearly show the effect of these high ratios on the *Required Bandwidth.*

[1] Symbol Rate is equal to the data rate for uncoded transmissions and the encoded bit rate for coded transmissions.

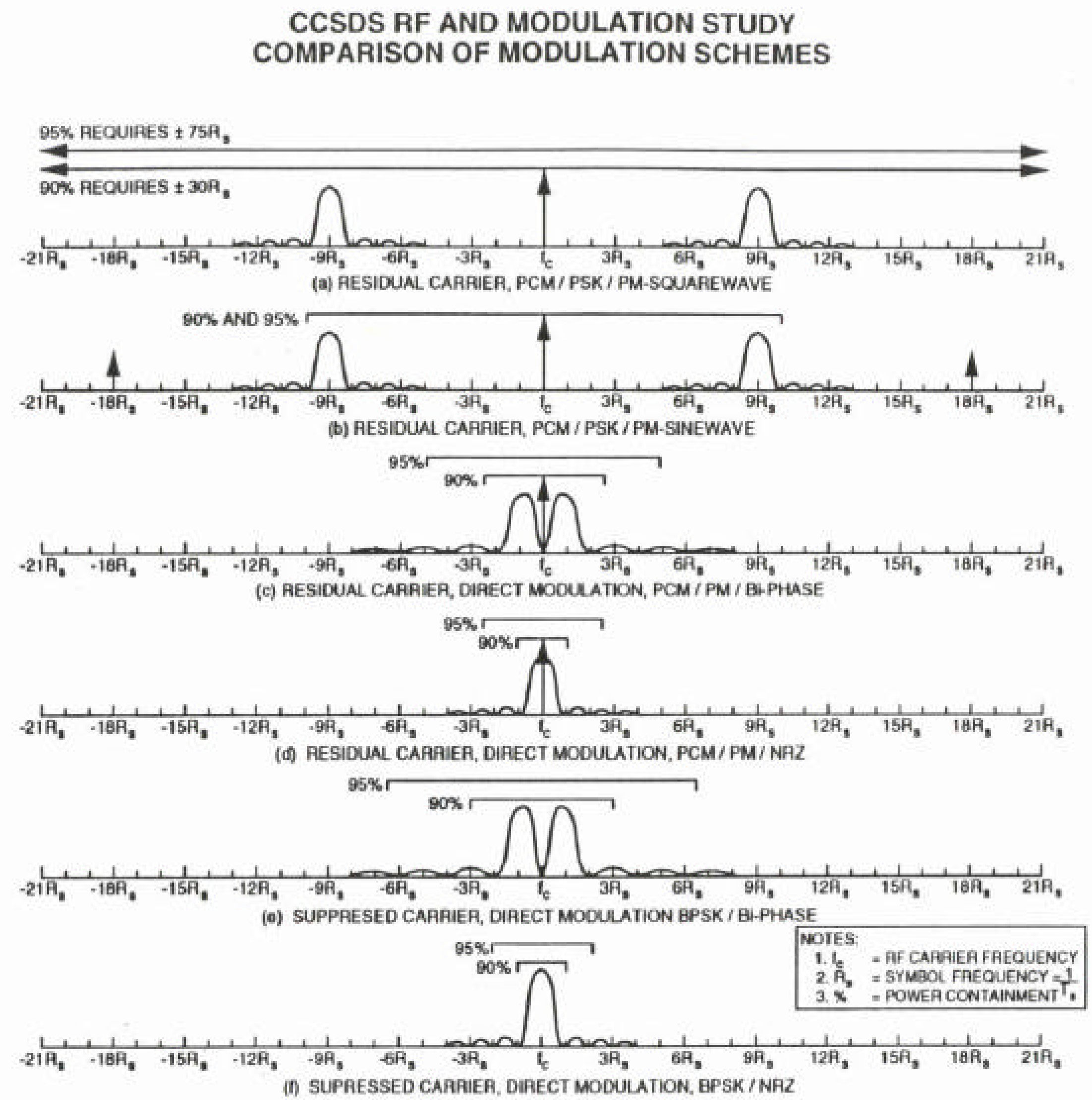

Figure 3-1. Spectra of Various Modulation Methods

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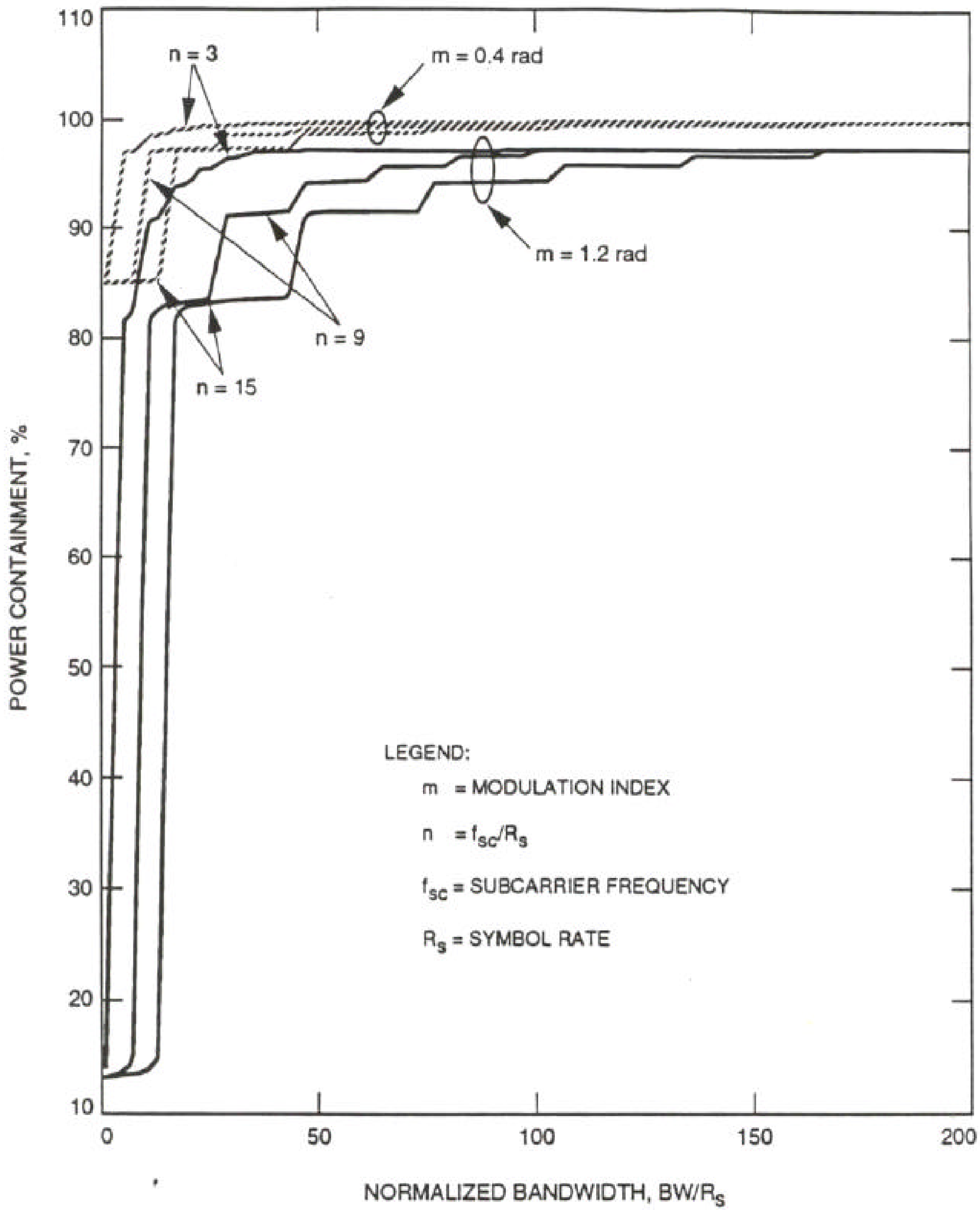

Figure 3-2. Bandwidth Needed for PCM/PSKPPM - Squarewave

For comparative purposes, the same reference points are used for evaluating both squarewave and sinewave subcarrier modulation methods (e.g., modulation index (m) = 1.2 radians and subcarrier frequency-to-symbol rate ratio (n) = 9). From Figure 3-2, it is clear that the *Required Bandwidth* is quite large for either 90% or 95% power efficiencies. Approximately 30 Rs and 75 Rs are required for the respective efficiencies. A summary of the results will be found in columns 2 and 3 of Table 3-2 at the end of this section.

As will be shown in 3.1.2, squarewave subcarriers consume substantially more bandwidth than do sinewave subcarriers. Although the modulation/demodulation losses are likely to be greater than for direct modulation schemes, most of the transmitted power is recoverable when using squarewave subcarriers, provided that the earth station receiver's bandwidth is sufficiently wide.

Squarewave subcarriers may still find application in some Category B missions where the data's symbol rate is low and significant data sideband power will fall into the RF carrier phase locked loop's bandwidth if a direct modulation scheme is used.

3.1.2 Sinewave Subcarriers

CCSDS Recommendation 401 (2.4.5) B-1 states that Category A missions should employ sinewave subcarriers. Congestion in the 2 GHz band, combined with the comparatively strong signals from Category A spacecraft, constrain each user to the minimum amount of spectrum necessary for his communication. Sinewave subcarriers require less spectrum bandwidth than do squarewave subcarriers. Although sinewave subcarriers have greater losses, and therefore are less efficient than squarewave subcarriers at high RF modulation indices, the stronger signals from Category A missions largely offset this disadvantage.

Figure 3-1 (b) depicts the frequency spectrum of a system utilizing a single sinewave subcarrier. Unlike the squarewave subcarrier's frequency spectrum, a sinewave subcarrier will have energy at the even harmonics in the form of a Delta function. The Delta function's amplitude will depend upon the RF carrier's modulation index. It is this energy that is lost during the demodulation process and which accounts for the lower efficiency of sinewave subcarrier systems.

Figure 3-3 shows the spectrum bandwidth for data systems using sinewave subcarriers. As with the squarewave subcarrier plot, the figure normalizes bandwidth to the data Symbol Rate, Rs (e.g., BW/Rs) and utilizes a subcarrier fequency-to-symbol rate ratio of 9. Some missions have flown ratios as high as 1,000. A brief glance at Figure 3-3 will clearly show the effect of these high ratios on the *Required Bandwidth*.

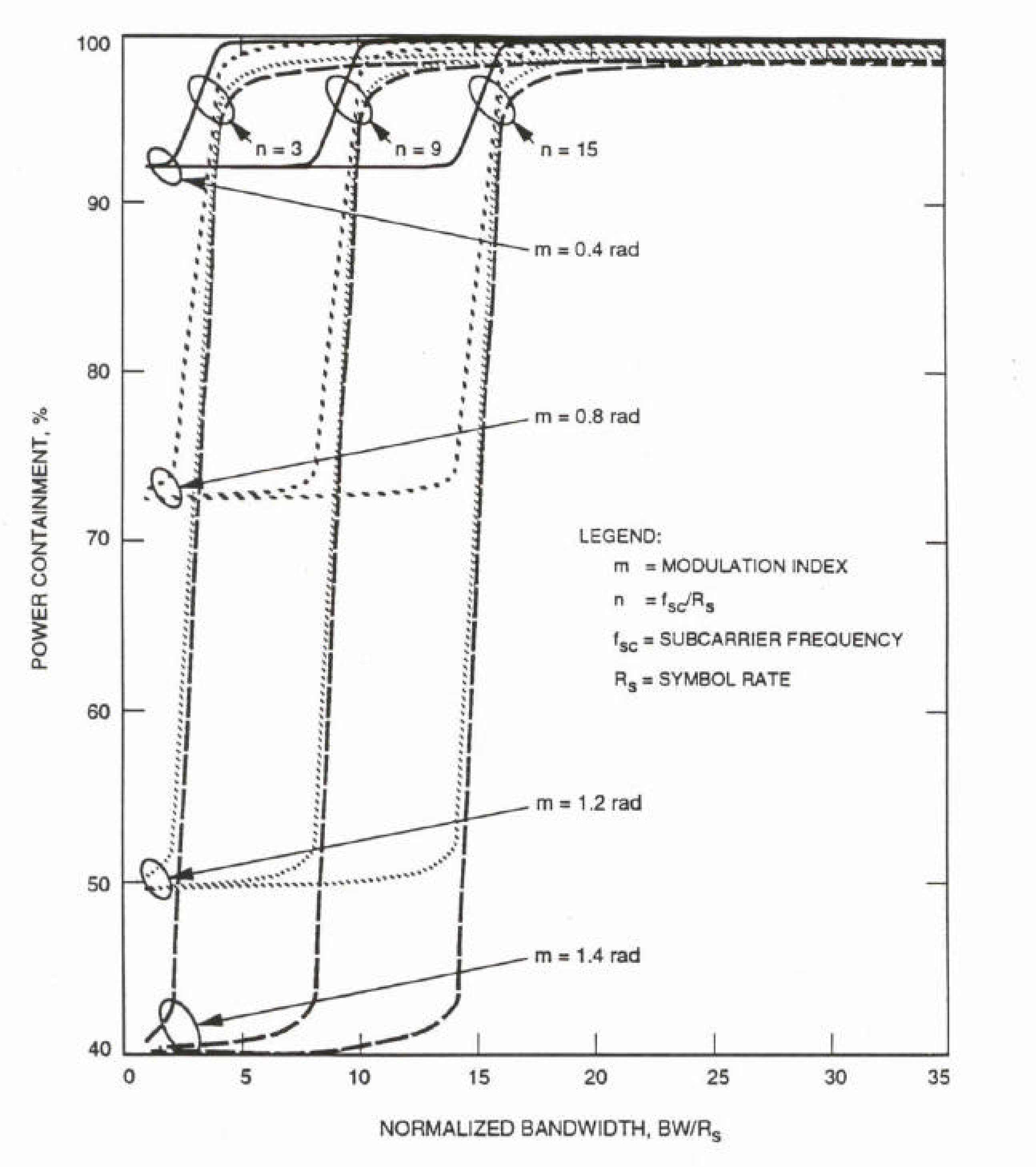

Figure 3-3. Bandwidth Needed for PCM/PSK/PM-Sinewave

For a mid-range value of n = 9 and a typical modulation index of 1.2 radians, the *Required Bandwidth* is about 10 times the Symbol Rate, Rs, for both the 90% and 95% Power Containments[2]. Note that a bandwidth approximately 30 times the Symbol Rate is required if the ITU's *Occupied Bandwidth* computation is used. Results of these computations will be found in columns 2 and 3 of Table 3-2.

Although using less bandwidth than squarewave subcarriers, the use of sinewave subcarriers does introduce greater losses than other modulation methods because of the high order Bessel functions, which become prominent at high modulation indices. Nevertheless, sinewave subcarriers may still find application in some Category A mission designs where the data's symbol rate is low and significant data sideband power will fall into the RF carrier phase locked loop's bandwidth.

3.2 Direct Modulation Schemes

As indicated in Table 3-1, several direct modulation schemes were considered. Historically, space agencies used residual carrier systems[3]. This provided a stable reference frequency at the earth station, which was used to demodulate the data from the carrier. Alternative, suppressed carrier systems will be considered following a discussion of traditional residual carrier systems. None of the modulation schemes considered in this section employ subcarriers.

Direct modulation schemes are inherently more bandwidth efficient than those employing subcarriers. This is due, in part, to the way that the ITU defined *Occupied Bandwidth* to be that span of frequencies, covered by the modulated signal, which excludes only the lower 0.5% and the upper 0.5% of the transmitted power. Thus, large frequency gaps between the RF carrier and the subcarrier are included in the *Occupied Bandwidth* calculation despite the fact that there is no significant modulation sideband energy in large portions of these frequency gaps.

3.2.1 Direct Modulation, Residual Carrier, Bi-ϕ

From a spectrum bandwidth perspective, direct modulation with a Bi-ϕ format is a compromise between direct modulation with an NRZ format and a conventional subcarrier telemetry system. It places the modulated data sidebands closer to the RF carrier while providing a null in the data's frequency spectrum at the RF carrier's frequency. Figure 3-1 (c) shows the PCM/PM/ Bi-ϕ spectrum, which ensures that the carrier will be easily distinguishable from the surrounding data sidebands. The bandwidth advantage of direct modulation schemes is readily apparent in this figure.

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[2] Power Containment is that percentage of the total modulated data's power contained in the indicated *Required Bandwidth* for each specific modulation index and subcarrier frequency-to-symbol rate ratio.

[3] Residual Carrier System is one in which the modulation index is less than ± 90 degrees so that a small percentage of the total transmitted power remains at the RF carrier frequency.

Sometimes called Manchester modulation, a Bi-ϕ format is formed by the modulo-2 addition of each data symbol with a squarewave clock whose period is equal to that of a data symbol. In addition to moving the data's spectrum away from the RF carrier's frequency, Bi-ϕ modulation also ensures RF carrier phase transitions during each data symbol.

With random data, this modulation scheme produces a spectrum with a clearly discernable RF carrier component and a $[(\sin^4 x)/(x)^2]$ distribution with peaks at about ± 0.75 Rs (Rs = symbol frequency, fs) due to the modulation. A null in the data's spectrum will lie at the RF carrier's frequency, fc. Additional nulls, on either side of fc will lie at ± 2 fs, ± 4 fs, ± 6 fs, etc. Figure 3-4 shows the spectrum bandwidth at various levels of power containment. For a modulation index, m, of 1.2 radians, *Required Bandwidths* of 2.5 Rs and 5 Rs are needed for 90% and 95% power containment respectively. A summary of the findings will be found in Table 3-2, columns 2 and 3.

Direct Bi-ϕ modulation is useful when bandwidth conservation is important and the modulated symbol rate is sufficient to ensure that the level of data sideband power, falling in the phase locked loop's bandwidth, is sufficiently low. This modulation scheme should find broad application in future missions having low or moderate data rates or where a stable carrier reference frequency is required.

3.2.2 Direct Modulation, Residual Carrier, NRZ

Direct NRZ differs from Direct Bi-ϕ modulation in that the double frequency clock component is absent in the former modulation type. Here, the modulated telemetry data's frequency spectrum is discern ably narrower than the one for Bi-ϕ modulation. The RF frequency spectrum for this modulation type will be found in Figure 3-2 (d). For random telemetry data, the power spectrum is described by $[(\sin x/x)^2]$. The peak of the spectrum occurs at the RF carrier's frequency, fc, and the nulls are at fc ± 1 fs, ± 2 fs, ± 3 fs, etc.

Clearly, the advantage of direct NRZ modulation is the substantially reduced bandwidth needed for communications as compared to the modulation types discussed above. Figure 3-5 shows the spectrum bandwidth for several levels of power containment. This is the most bandwidth efficient modulation method considered so far. Table 3-2, columns 2 and 3 list the *Required Bandwidths* for 90% and 95% power containments respectively.

PCM/PM/NRZ modulation suffers the disadvantage of placing the peak of the data's frequency spectrum at the RF residual carrier's frequency. Unless the data symbol rate is comparatively high, so as to spread the data sideband's power over a relatively broad frequency range, the RF carrier may be difficult to detect. Additionally, the presence of data power within the earth station's phase locked loop's bandwidth can introduce RF carrier interference with the result that the loop's phase jitter is increased.

PCM/PM/NRZ also suffers a second disadvantage. Data streams containing significant imbalances in 1s and 0s (imbalance in Mark-to-Space ratio) can adversely affect the performance of a PCM/PM/NRZ system (Reference 5). Figure 3-6 shows the effect upon

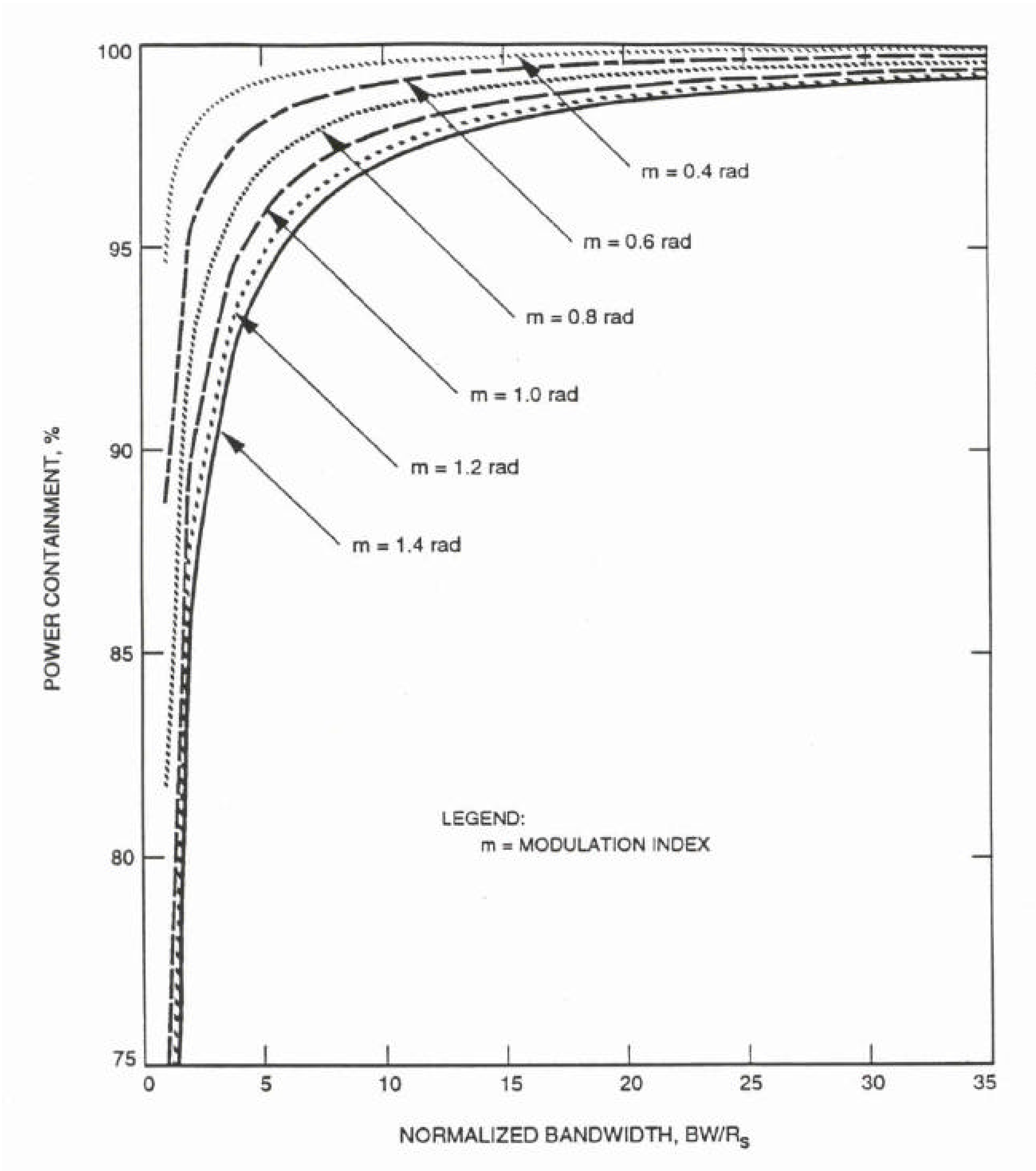

Figure 3-4. Bandwidth Needed for PCM/PM/Bi-Phase

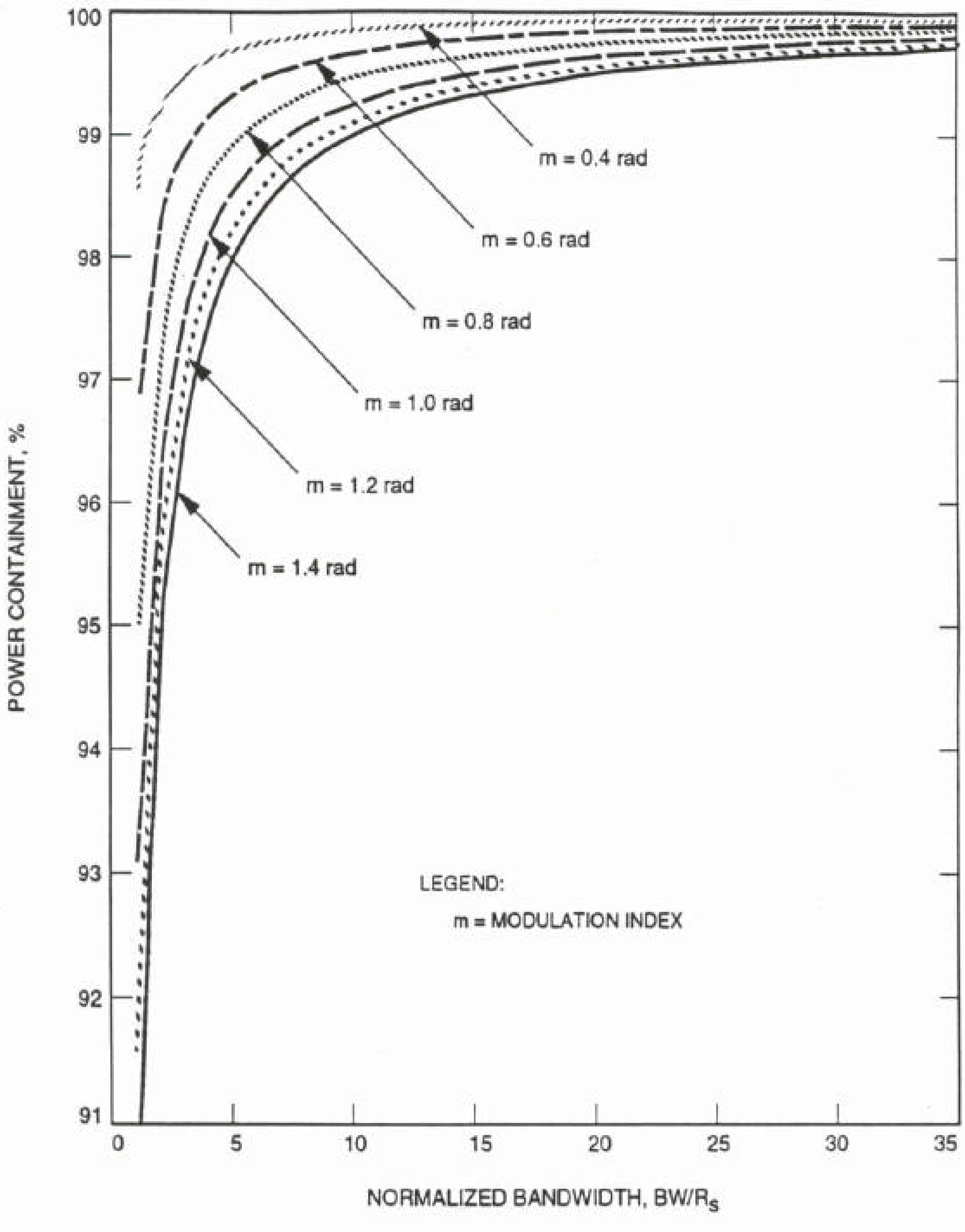

Figure 3-5. Bandwidth Needed for PCM/PM/NRZ

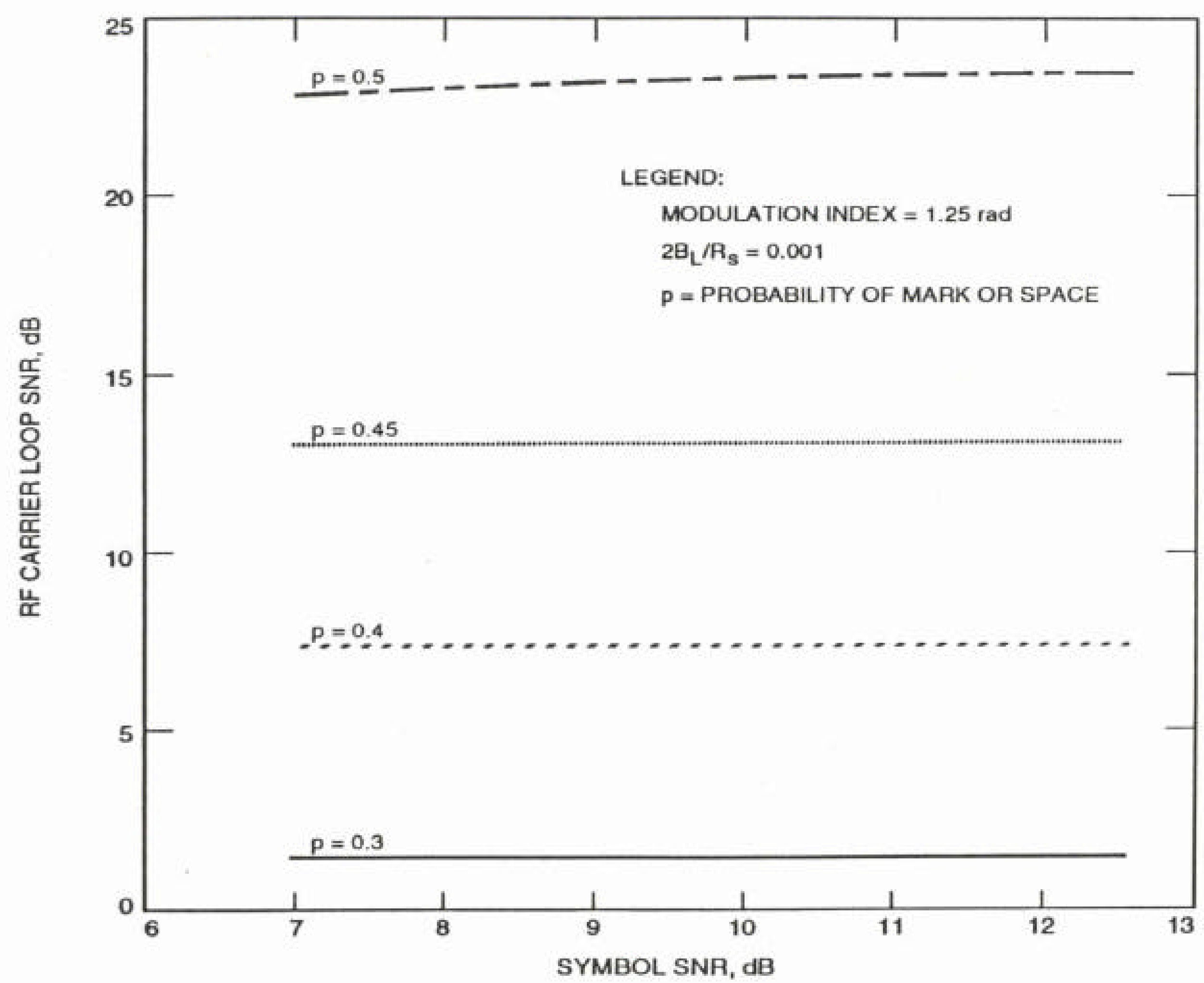

Figure 3-6. Effect of Unbalanced Data on RF Carrier Loop SNR for PCM/PM/NRZ Modulation

Signal-to-Noise Ratio (SNR) in the residual carrier's Phase-Locked-Loop resulting from an imbalanced data stream. Here, a p = 0.5 means that a 1 (Mark) or a 0 (Space) are equally likely. System performance was evaluated at an RF modulation index of 1.25 radians and a Phase-Locked-Loop Bandwidth/Telemetry Symbol Frequency Span ratio of 0.001. A Phase-Locked-Loop SNR of 23 db for balanced data (e.g., p = 0.5) will be degraded by more than 15 dB when the probability of a Mark (or a Space) is reduced from 0.5 to 0.4.

At high modulation indices, little power is left in the residual carrier. Imbalances in the Mark-to-Space ratio of the modulated NRZ data produce a component at the RF carrier's frequency which has a randomly varying phase with respect to that RF carrier. This "*dc-component*" results in interference to the residual RF carrier which has the effect of lowering the SNR in the carrier tracking loop, particularly as the imbalance increases and the "*dc-component*" becomes significant with respect to the carrier component's amplitude. As the carrier Phase-Locked-Loop's phase jitter increases, data demodulation efficiency drops. This "Radio Loss" or "Phase Jitter" loss must be assessed to accurately predict the telecommunications channel's performance. Demodulation efficiency resulted in the CCSDS Recommending a minimum carrier tracking loop SNR of 15 dB at high modulation indices.

The resulting degradation to the telemetry data channel's performance for large Mark-to-Space ratio imbalances in a PCM/PM/NRZ system is clearly evident in Figure 3-7. This figure shows the effect upon Symbol Error Rate (SER) and Symbol Signal-to-Noise Ratio (SNR) as the Probability of a Mark is reduced. Modulation indices and bandwidth ratios are identical to those used for the analysis of the carrier tracking loop above. With a probability of Mark-to-Space = 0.45 the telemetry data system experiences a loss of about 0.3 dB when compared to a perfect data stream. But, a Mark-to-Space = 0.4 produces a several dB loss. Additionally, the Symbol Error Rate becomes substantially invariant with Symbol SNR.

Figure 3-8 shows that a PCM/PM/NRZ system's performance is particularly sensitive to modulation index. Specifically, Mark-to-Space ratio imbalances result in significantly greater system losses at high modulation indices than at low ones. This result follows from the fact that, at low modulation indices, significantly more power is retained in the residual RF carrier so that the SNR degradation, resulting from the "*dc-component*" produced by imbalanced data, is lower. Therefore, if the Mark-to-Space ratio falls to 0.4, then modulation indices should be kept at or below 1 radian.

This sensitivity of PCM/PM/NRZ modulation to data imbalances means that it should be used with extreme care to ensure that the system is operating in a region where the losses due to telemetry data imbalances are acceptable. Convolutional coding will help to restore a balance between 1s and 0s, but if such coding is inadequate, due to the nature of the raw telemetry data, then a data randomizer, such as the one recommended by the CCSDS, or some other means to reduce the effects of data imbalances should be employed (Reference 6).

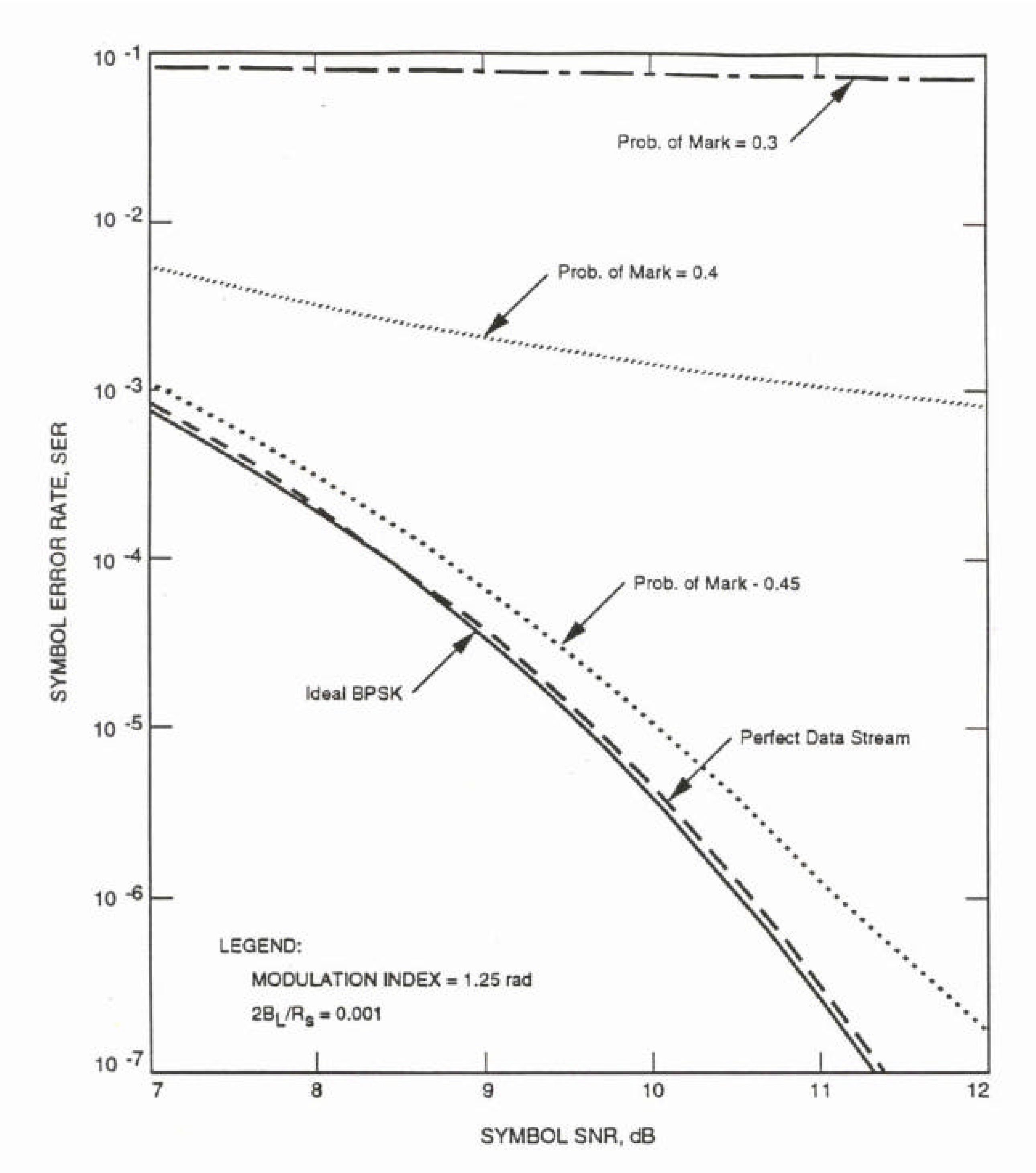

Figure 3-7. Effect of Unbalanced Data on Telemetry Symbol Error Rate for PCM/PM/NRZ

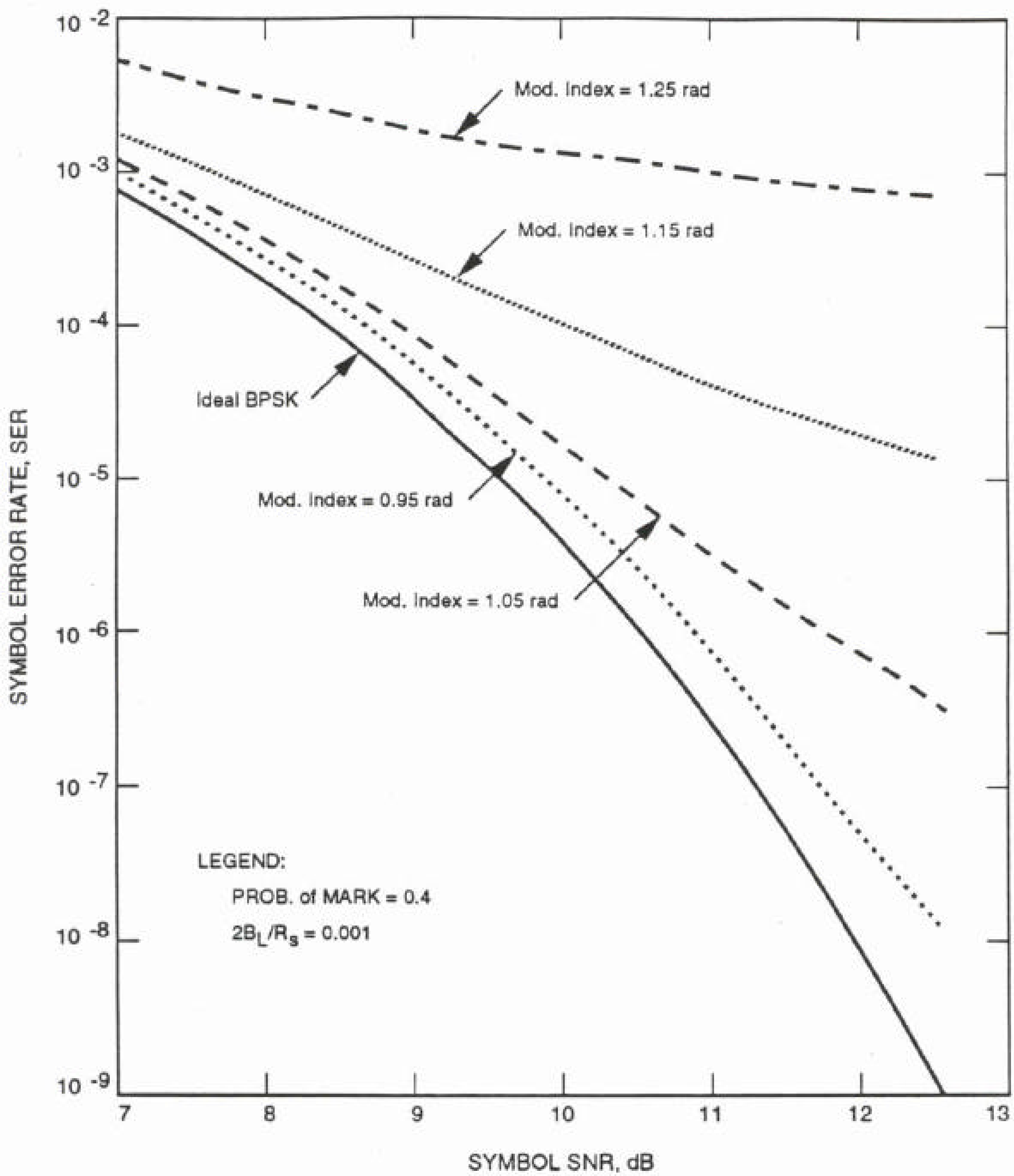

Figure 3-8. Effect of Modulation Index on Symbol Error Rate with Unbalanced Data for PCM/PM/NRZ Modulation

Direct NRZ modulation should find application to residual carrier systems where minimum bandwidth utilization is important, when the data rates are moderate to high, and when there is a good balance between 1s and 0s in the modulated telemetry data stream. When using this modulation type, care must be exercised to ensure that the carrier is sufficiently distinguishable for RF carrier acquisition at the earth station's receiver. Some earth stations may prefer that the telemetry modulation be turned off during the acquisition process. Other earth stations, using a spectrum analyzer in their receiver acquisition system, may experience no difficulty in acquiring the RF carrier with telemetry modulation turned on.

One of NASA's International Solar Terrestrial Physics (ISTP) program's spacecraft named Polar uses this modulation scheme. Polar is an earth orbiter, has a residual carrier, and a data rate of 500 kb/s. A rate ½, constraint length 7 convolutional code concatenated with a Reed-Solomon code increases the symbol rate to slightly above 1 Ms/s. This spacecraft will be launched in mid 1994.

3.2.3 Suppressed Carrier, Bi-Phase Shift Keyed (BPSK/Bi-ϕ)

BPSK/Bi-ϕ modulation fully suppresses the RF carrier by modulo-2 adding the telemetry data to a squarewave clock at twice the telemetry symbol's frequency and modulating the RF carrier with and index of $\pm$ 90 degrees. In this regard, the system is similar to the one described in section 3.2.1 above. Like that modulation scheme, the data's spectrum will follow a $[(\sin^2 x)/(x)^2]$, distribution with peaks at $\pm$ 2 fs, $\pm$ 4 fs, $\pm$ 6 fs, etc. and a null at the carrier's frequency. However, unlike direct residual carrier Bi-ϕ modulation, there will be no residual RF carrier component. The BPSK/Bi-ϕ spectrum is shown in Figure 3-2 (e).

A carrier component is reestablished within the earth station receiver's Costas or Squaring Loop. The result is that all of the transmitted power is placed in the data's sidebands. Since the RF carrier is reconstructed from the data sidebands, virtually all of the transmitted power is available for this purpose as well.

Costas Loops regenerate the RF carrier by combining signals detected in a reference and a quadrature channel. Noise, as well as signal is present in both channels and both are combined. As a consequence, it is important to have a sufficient Signal-to-Noise Ratio (SNR) in the loop. A minimum SNR of 12- 15 dB is recommended for such loops.

Figure 3-9 shows the spectrum bandwidth as a function of power containment. Note that the *Required Bandwidth* is slightly greater for this modulation type than for the residual carrier PCM/PM/Bi-ϕ owing to the lack of RF carrier. This slightly larger Required Bandwidth appears in Table 3-2.

BPSK/Bi-ϕ modulation will find application in high data rate systems where conservation of bandwidth is important and where maximum system performance is required. Some comparatively low rate missions (Galileo-S-Band, Pluto Flyby, and MESUR) are considering the use of BPSK modulation.

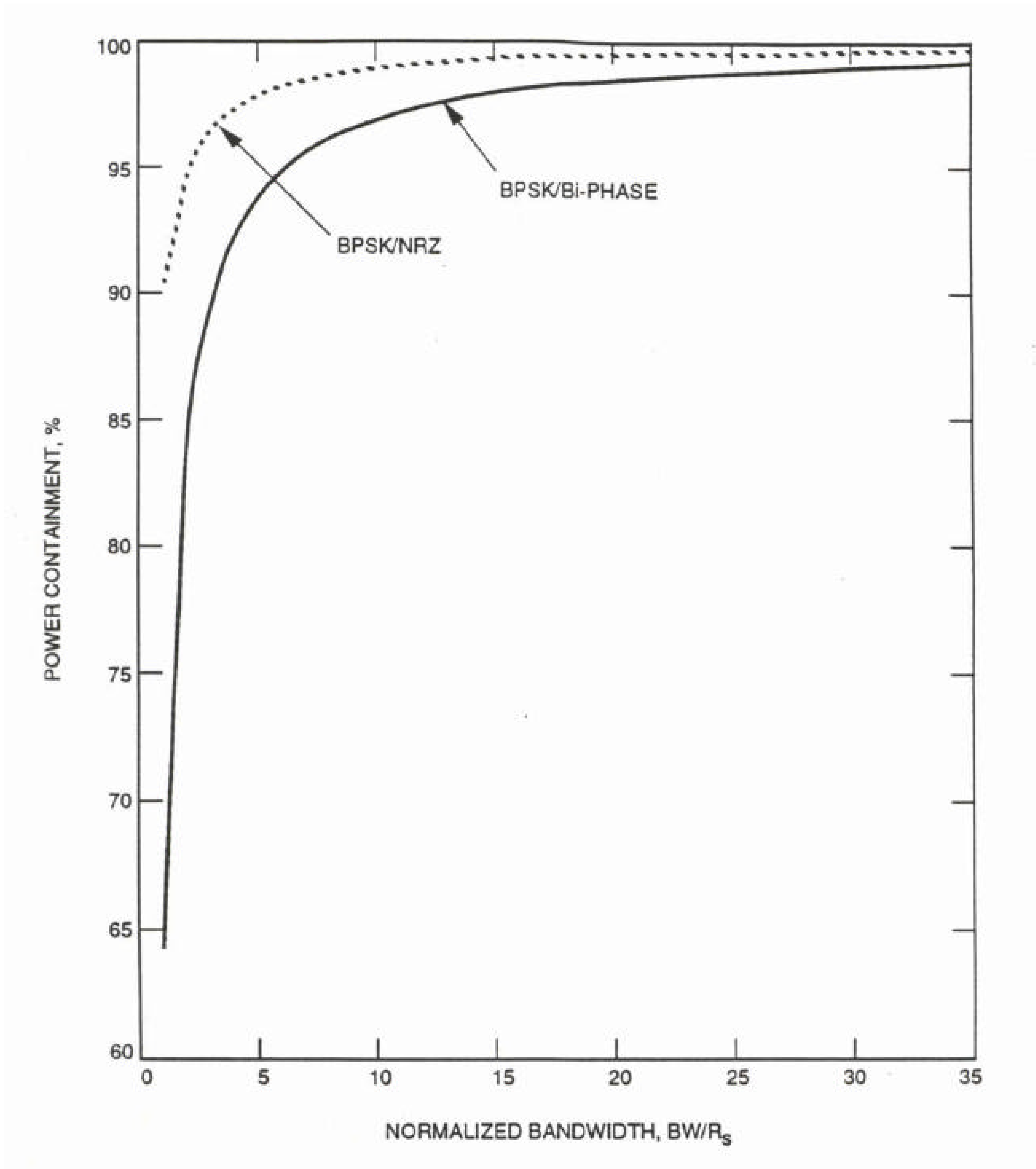

Figure 3-9. Bandwidth Needed for BPSK Signals

3.2.4 Direct Modulation, Suppressed Carrier, NRZ (BPSK/NRZ)

Like direct residual carrier modulation, BPSK/NRZ differs from BPSK/Bi-ϕ in that the double frequency clock component is absent in the former modulation type. In all other respects, BPSK/NRZ is the same as BPSK/Bi-ϕ discussed above. The modulated signal's frequency spectrum is shown in Figure 3-2 (f). It reflects the bandwidth conserving nature of NRZ modulation. Figure 3-9 demonstrates the bandwidth efficiency of BPSK/NRZ modulation as compared with BPSK/Bi-ϕ modulation.

Given the sensitivity of a PCM/PM/NRZ system's performance to imbalances between 1s and 0s in the data stream, a question arises as to whether BPSK/NRZ systems have the same problem. Studies are underway to analyze and simulate the performance of these systems in the presence of imbalanced data.

BPSK/NRZ modulation will find application in moderate to high data rate telemetry data systems where bandwidth conservation is of importance, where there is a possibility that the modulated data symbols may contain an imbalance between 1s and 0s, and where the complexities of QPSK and N-PSK modulation methods are to be avoided.

4.0 EFFECT OF SPECTRUM SHAPING

Spectrum shaping of the radiated signal is implicit in the notion of *Required Bandwidth.* Depending upon the flight radio system's architecture, the suggested concept may introduce a small loss in transmitted power in order to obtain a significant saving in bandwidth. Spectrum shaping should be accomplished so as to minimize the size, weight, and power losses due to any additional components. Options for spectrum shaping were shown in Figure 2-1.

If bandwidth restriction becomes excessive, whether at the transmitter or receiver, additional losses can be introduced. When the bandwidth is restricted to less than the main lobe of the transmitted data's frequency spectrum, then the shape of the transmitted pulse is changed. Symbols are elongated with the result that one symbol will begin to overlay the following symbol (Reference 1). Termed Intersymbol Interference (ISI), the effect is a loss in symbol energy resulting in a reduced telemetry SNR.

ISI was evaluated for three bandwidths equivalent to ± 1 Rs, ± 2 Rs, and ± 5 Rs (Reference 1). The results will be found in columns 4, 5, and 6 of Table 3-2. Since all spectrum shaping was assumed to be at the spacecraft, actual bandwidth, sufficient to handle one, two, or five times the main spectral lobe(s) were used. Transmitter bandwidths are listed below the losses in the ISI columns of Table 3-2. These filter bandwidths also provide an easy method for comparing the *Required Bandwidths* of the several modulation methods.

TABLE 3-2: PERFORMANCE SUMMARIES OF MODULATION SCHEMES

Modulation Type	90% Power Containment	95% Power Containment	ISI SNR Reduction dB	ISI SNR Reduction dB	ISI SNR Reduction dB	In-Band Interference Susceptibility
PCM/PSK/PM (Sq) n = 9, m = 1.2 rad.	± 30 R_s	± 75 R_s	0.75 @ ± 10 R_s	0.15 @ ± 20 R_s	0.01 @ ± 50 R_s	Less susceptible than PCM?PSK/PM Sine by about 4 dB. Susceptible to Out-of-Band Interference.
PCM/PSK/PM (Sine) n = 9, m = 1.2 rad.	± 10 R_s	± 10 R_s	0.75 @ ± 10 R_s	0.18 @ ± 20 R_s	0.04 @ ± 50 R_s	More susceptible than PCM/PSK/PM Square.
PCM/PM/Bi-f m = 1.2 rad.	± 2.5 R_s	± 5 R_s	6.3 @ ± 1 R_s	0.34 @ ± 2 R_s	0.20 @ ± 5 R_s	No information available.
PCM/PM/NRZ m = 1.2 rad.	± 1.2 R_s	± 2.5 R_s	0.85 @ ± 1 R_s	0.21 @ ± 2 R_s	0.01 @ ± 5 R_s	No information available.
BPSK/Bi-f m = ± 90 deg.	± 3 R_s	± 6.5 R_s	6.3 @ ± 1 R_s	0.29 @ ± 2 R_s	0.15 @ ± 5 R_s	Less susceptible than QPSK. No information available comparing to modulation types listed above.
BPSK/NRZ m = ± 90 deg.	± 1 R_s	± 2 R_s	0.74 @ ± 1 R_s	0.17 @ ± 2 R_s	0.04 @ ± 5 R_s	Likely to be more sensitive than BPSK/Bi-f. No information available as to other modulation types.

5.0 SUSCEPTIBILITY TO INTERFERENCE

Reference 3 reviewed the literature to determine whether any comparative studies of susceptibility to interference could be found. Very little information was discovered. The data that was found tended to compare the susceptibility of similar systems rather than different modulation schemes. Results are summarized in column 7 of Table 3-2. For example, data was found comparing squarewave and sinewave subcarrier systems. Another study measured the relative performance of BPSK and QPSK systems. None were located which contrasted subcarrier and direct modulation methods.

Despite this lack of information, some simple observations can be made. Generally, the larger the frequency spectrum's width, the less the susceptibility to in-band interference. This results from the logical assumption that individual interference bursts tend to be concentrated in narrow frequency ranges. Therefore, the larger the width of the transmitted data's frequency spectrum, the less susceptible it is to interference in a portion of that band.

This "rule" is one reason why squarewave subcarriers have a distinct advantage over some of the other modulation techniques. Of course, other methods such as high rate convolutional coding and spread spectrum modulation can be used to achieve the same result with any of the direct modulation methods. However, the important point is that restricting the frequency spectrum's width increases the susceptibility to in-band interference.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Because of the difficulties with the ITU definitions for *Occupied Bandwidth* and *Necessary Bandwidth*, it is recommended that both the CCSDS and SFCG adopt a new definition for *Required Bandwidth* based upon the proposal in Section 2.3. Because spectrum shaping is intrinsic in the concept of *Required Bandwidth*, the definition should specify the percentage of power containment (acceptable loss). A suggested level of 95% (-0.2 dB) is recommended for *Required Bandwidth*.

With regard to modulation schemes, it is recommended that subcarriers should be eliminated from flight systems except in those unusual cases where they are required for some valid technical reason. The excessive amount of bandwidth required by subcarrier modulation systems is graphically summarized in Figure 6-1. Instead, one of the direct modulation schemes described above, together with CCSDS recommended Virtual Channels (Reference 4) should be used to separate the data streams. The CCSDS and SFCG should immediately consider limiting the use of subcarrier modulation schemes, except in specified circumstances.

Where bandwidth conservation is important, and particularly in high data rate systems, special consideration should be given to PCM/PM/NRZ and BPSK/NRZ formats[4]. *Required Bandwidths*

[4] Provided that there is a good balance in the modulated data stream's 1s and 0s (Mark-to-Space ratio).

for the several direct, residual carrier, modulation schemes are shown in Figure 6-2. If spectral spreading is needed to meet PFD limitations, then consideration should be given to reducing the transmitter's power and using convolutional encoding to compensate for the diminished power and to spread the spectrum.

After the study of all candidate modulation schemes are completed (including QPSK, OQPSK, and MSK), both the CCSDS and SFCG should coordinate and consider adopting Recommendations favoring specific direct modulation methods. It is likely that the recommended types of modulation will be a function of mission design and data rate.

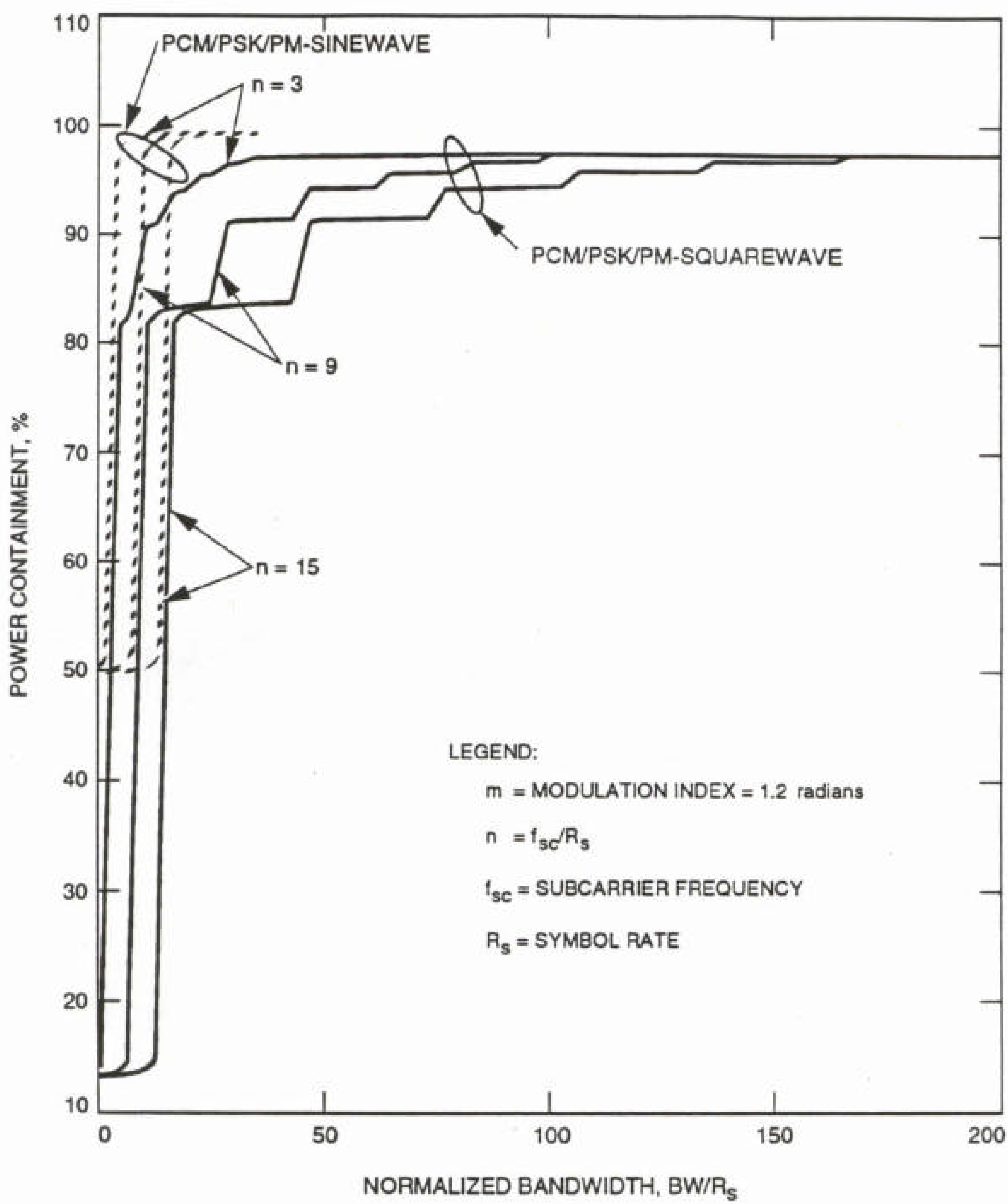

Figure 6-1. Comparison of PCM/PSK/PM Modulation Types

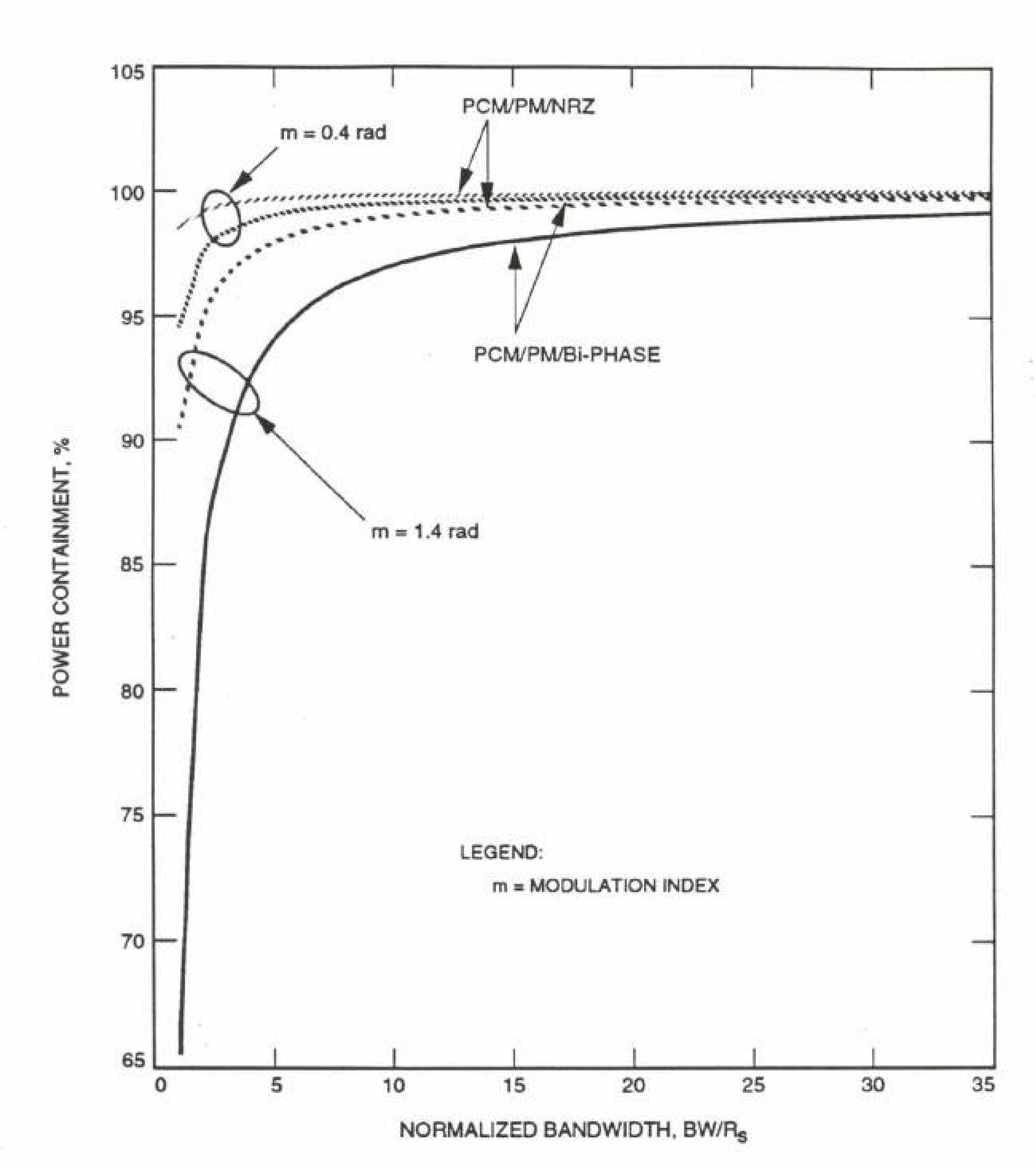

Figure 6-2. Comparison of PCM/PM Modulation Types

REFERENCES

1. *Required Bandwidths and Unwanted Emissions for Residual and Suppressed Carrier Systems*, Tien M. Nguyen, Jet Propulsion Laboratory, September 1993.

2. *Crosstalks in QPSK Communications Systems*, Tien M. Nguyen, Jet Propulsion Laboratory, September 1993.

3. *A Review of the Current Available Studies for the Interference Susceptibility of Various Modulation Schemes*, Tien M. Nguyen, Jet Propulsion Laboratory, September 1993.

4. Consultative Committee for Space Data Systems, Recommendations for Space Data System Standards, *Packet Telemetry*, CCSDS 102.0-B-2, January 1987.

5. *Behavior of PCM/PM Receivers in Non-Ideal Channels; Part 1: Separate Effects of Imperfect Data Streams and Bandlimiting Channels on Performance*, Tien M. Nguyen, Jet Propulsion Laboratory, September 1993.

6. *Unbalanced Data Compensation Techniques for PCM/PM Receivers*, Tien M. Nguyen and Sami M. Hinedi, Jet Propulsion Laboratory, February 1993.