②

STUDY OF
RADIO PROGRAM DISTRIBUTION BY
DIRECT BROADCAST SATELLITE

FINAL REPORT

MCS MILLER COMMUNICATIONS
SYSTEMS LTD.

Checked 11/

② STUDY OF
RADIO PROGRAM DISTRIBUTION BY
DIRECT BROADCAST SATELLITE
FINAL REPORT

MCS File No: 8131
DSS Contract No.: 0ST80-00159
Date: October 22, 1981

Prepared By: ①
R. Chang and P. Coverdale

Approved By:
R. Lyons

SUBMITTED BY:

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Background

Although radio broadcast services are extensive and well established in the major population centers, generally located along the "southern corridor" of Canada, such is not the case in the northern and remote areas of Canada where, in fact, the exact opposite is true. This situation is ameliorated to some extent by the Northern Service of the CBC which currently provides radio service to some 46 remote communities in the Northwest Territories and the Yukon Territory by utilizing a network comprised of terrestrial microwave radio facilities, off-the-air rebroadcast repeaters, troposcatter links and 4/6 GHz communication satellite facilities. The primary means of radio program broadcasting is, however, by shortwave (3 to 30 MHz) radio transmissions which are inevitably beset by the same problems associated with HF point-to-point communications in Canada.

The CBC Northern Service currently utilizes a single, concomitant, radio program carrier in each televison transponder on a time-shared basis in order to provide national network programming material from the south to its regional production centers in the Yukon Territory and N.W.T. as well as for regional broadcasting. The heavy demand placed on this limited resource has, on occasions, resulted in double-illumination of the satellite due to a lack of adequate network control. In light of this, the feasibility of increasing the number of radio program carriers accessing each of the TV transponders on Anik B has been extensively investigated [1]. The major source of activity, however, in the use of satellites to provide network program feeds to local radio broadcast stations is presently occurring in the U.S.A. where SCPC technology has been utilized extensively by such organizations as the

National Public Radio (NPR) and Mutual Broadcasting to distribute high-quality monophonic and stereophonic programs (by using two SCPC carriers) on a continental U.S. (CONUS) basis using presently available 4/6 GHz satellite technology.

With the success of the Hermes experiments and the field trials (on-going) on the Anik B satellite, the feasibility of direct-to-home television service via higher power satellites has been clearly established and has paved the way for further development towards a direct broadcast satellite (DBS) [2] in the post-Anik C era. The Anik B field trials have, in fact, established the plausibility of a lower power DBS-type satellite [3], [4] and this has instigated consideration of the Anik C satellite as a precursor to a Canadian DBS satellite for providing "interim DBS" service to individual homes and community receivers [5].

While the primary service of interest in the institution of a DBS service has been television, a logical extension would be to augment this by providing radio programming of national and regional interests. It is this augmentation of high-quality monophonic and stereophonic radio programming to an assumed existing DBS infrastructure which forms the basis of the investigation undertaken herein.

1.2 Purpose of the Study

The conduct of this study was divided into two consecutive phases (Phase I and II), spanning a total duration of approximately 8 weeks, with the outcome of Phase I dictating the thrust and direction of the ensuing Phase II. This report documents the combined results of Phase I and Phase II.

1.2.1 Phase I

The purpose of Phase I of the study was threefold:

1. To review previous and on-going research within the DOC and other Canadian agencies (e.g., Telesat Canada, CBC);
2. To review the literature with particular emphasis on work in progress or reported in the U.S.A., Europe and Japan;
3. To consider novel alternative approaches.

The general objective was thus to conduct a fairly comprehensive but qualitative survey of candidate distribution techniques from which the more promising approaches might be subjected to more detailed examination (Phase II) to determine the overall DBS system impact.

1.2.2 Phase II

Prior to commencing Phase II, the output of the Phase I study was evaluated to identify the more promising techniques within a DBS scenario. Further in-depth treatment of those techniques identified was to be undertaken in Phase II.

Specifically, the objectives of the Phase II study were to:

1. Perform detailed technical analysis of the selected approaches identified in Phase I with a view to determining those facts which might have the greatest impact on
   (a) the incremental cost of the DBS receiver and the overall system economics;

(b) compatibility with envisaged TV direct-broadcast systems and TV and radio receive equipment;

(c) System performance, receiver performance and operational flexibility;

(d) System capacity and growth potential.

Within this same context, key system parameters (e.g., oscillator long-term and short-term (phase noise) stability, receiver G/T, system margins, etc.) which could have an impact on the complexity and cost of the receiver were identified.

2. To delineate those features (e.g. growth flexibility, compatibility with existing terrestrial systems, amenability to regional programming, etc.) which would assist in evaluating the relative merits and demerits of each selected technique.

3. To address the effectiveness of each approach in responding to special Canadian needs and in fostering the development of Canadian industry for such equipment.

1.3 Terms of Reference

The DBS service scenario under which this study was undertaken is one in which there is an assumed need for augmenting a DBS television distribution service planned for the late 1980 time frame. The system is intended to provide high-quality monophonic and/or stereophonic radio program channels to either remotely located northern communities or to isolated communities which may be just beyond the service area of populated centers and hence are subject to varying or unacceptable grades of service.

Since both regional and/or national programs may be of interest to listeners, the transmission techniques by which such program materials, originating from diversely located program origination centers, have a great impact on the complexity, cost and expansion flexibility of the radio receiver which must be retrofitted to an existing DBS TVRO.

While the primary interest is in the evaluation of a direct-to-home radio broadcast system, the alternative of a higher cost, and therefore higher performance, "community receiver" has not been precluded.

Evaluations were conducted within the context of a presently envisaged Canadian DBS system (all-Canada coverage through the use of 6 spot beams) but results obtained are applicable to utilizing the Anik C satellite with its 4 spot beam coverage pattern [6] to provide interim DBS radio service.

Initial guidelines for the study are stated below:

1. 1 to 20 radio broadcast channels;

2. A range of audio signal-to-noise ratios (SNR) comparable to conventional off-the-air FM broadcasts;

3. Audio bandwidth of 15 kHz ("high-quality" audio);

4. Monophonic and stereophonic transmissions;

5. Analog and digital approaches to both baseband processing and carrier transmission techniques;

6. TV/Radio transponder sharing techniques including:

   (a) TV plus sound subcarrier(s) in the same transponder;
   (b) FDMA access to the same transponder by TV and radio program carrier(s);
   (c) TV and radio program carrier(s) in separate transponders.

2.0 CANDIDATE BASEBAND PROCESSING AND MULTIPLEXING TECHNIQUES

This section of the report gives a brief overview of the various techniques which are available for baseband processing and multiplexing of sound program channels into a form suitable for transmission via a DBS system. Many of these techniques are already in current use as a means of combining video and audio program sources for network feeds, and even terrestrial broadcasting.

2.1 Radio program Characteristics

Conventional radio broadcasting takes place in the medium wave, shortwave and VHF broadcast bands using either amplitude or frequency modulation of a radio frequency carrier by the audio source material. As a starting point in the choice of processing and multiplexing techniques for radio program distribution by satellite, it will be convenient to review the characteristics of the audio source material itself by examining the performance requirements of a communications channel which is designed to carry such source material, i.e., a radio program channel.

2.1.1 Program Channel Performance Requirements

Program channels are generally divided into three categories corresponding to the nominal channel bandwidth. AM broadcast feeds are typically 5 kHz and 8 kHz circuits, whereas FM stations use 15 kHz circuits. As already indicated, for the purposes of this study we will be most interested in the provision of high-quality audio circuits of 15 kHz bandwidth. CCITT defines the performance requirements for such circuits in Rec. J.21 [9], the important parameters of which (for a monaural signal) are given below in Table 2.1. In addition to the above, stereo transmission implies additional performance requirements to ensure similarity between left and right channels. These requirements, also from CCITT Rec. J.21 (and [10]), are given below in Table 2.2.

Frequency Response:

40 Hz	to	125 Hz	+0.5 to -2.0 dB
125 Hz	to	10 Hz	+0.5 to -0.5 dB
10 kHz	to	14 kHz	+0.5 to -2.0 dB
14 kHz	to	15 kHz	+0.5 to -3.0 dB

Maximum noise level:

Unweighted	- 41 dBmOs
Weighted (CCIR Rec. 468-1)	- 47 dBmOps*

Group Delay distortion:

40 Hz	55ms
75 Hz	24ms
14 kHz	8ms
15 kHz	12ms

Nonlinear distortion:

	Total harmonic distortion	2nd-3rd harmonics
40 Hz to 125 Hz	1%	0.7%
125 Hz to 7.5 kHz	0.5%	0.35%

*This corresponds to a peak signal to weighted noise ratio of 56dB.

TABLE 2.1 MAJOR PARAMETERS FOR 15kHz SOUND PROGRAM CIRCUITS (MONOPHONIC)

Maximum difference in gain between A and B channels:

40 Hz to 125 Hz	1.5 dB
125 Hz to 10 kHz	0.8 dB
20 kHz to 25 kHz	3.0 dB

Maximum phase difference between A and B channels:

40 Hz	30^0
40 Hz to 200 Hz	straight line segment on scale linear in degree and logarithmic in frequency
200 Hz to 4 kHz	15^0
4 kHz to 14 kHz	straight line segment on scale linear in degree and logarithmic in frequency
14 kHz	30^0

Crosstalk ratio between A and B channels

Intelligible	40 Hz to 15 kHz	50 dB
Nonlinear	40 Hz to 15 kHz	60 dB

TABLE 2.2 REQUIREMENTS FOR 15 kHz STEREO PROGRAM CIRCUITS

It is evident that the requirements given above are fairly stringent, but it should be remembered that they relate to individual 15 kHz sound program circuits, several of which may be used in tandem to interconnect various facilities in a broadcast network, i.e., studio to studio, studio to transmitter site, etc. In other words, the requirements for individual circuits are made stringent so that the overall performance may still fall within tolerable limits. In a DBS environment, it may be argued that the requirements could be relaxed somewhat, so long as the final signal arriving at the subscriber is comparable (or better) than from conventional broadcasting. This level of performance is much more loosely defined. Nevertheless it is reasonable to aim for a DBS sound system which provides comparable quality to domestic "hi-fi". In this regard, the most important criteria are that the overall frequency response should be within ±1 dB from 100 Hz to 10 kHz, and be no more than 3 dB down at 15 kHz, and the peak signal-to-weighted noise ratio should be at least 56 dB (see Table 2.1). These two requirements will be especially relevant when considering digital encoding schemes.

2.2 Analog and Digital Processing Techniques Applicable to a Sound Program Channel

2.2.1 Analog

Although it is fundamentally undesirable to alter in any form the characteristics of the audio program material, it is possible to make use of analog processing techniques to improve the signal-to-noise performance of the communication channel. Two techniques are in common use, one taking advantage of the frequency spectrum characteristics of the input signal and the other the amplitude characteristics.

i) Pre-emphasis/De-emphasis

In this technique, which is universally employed in VHF-FM broadcasting, additional amplification (pre-emphasis) at the rate of 6 dB/octave is applied to the high frequency end of the audio spectrum prior to transmission. At the receiver, a network having the inverse frequency characteristics (de-emphasis) is used to restore the baseband signal. However, any noise which has been added by the communications medium will also be attenuated at the higher frequencies. Since FM noise usually has dominant high-frequency components, the noise will be attenuated relative to the signal and an improvement in signal-to-noise ratio will result. An improvement of over 13 dB in signal-to-noise ratio by means of pre-emphasis/de-emphasis has been quoted for an FM channel [11].

The actual pre-emphasis/de-emphasis characteristic is usually described in terms of the time constant of a simple RC network used to provide the characteristics. A value of 75 μs (corresponding to a 3 dB point of 2.1 kHz) is employed in FM broadcasting in North America. One minor disadvantage of pre-emphasis/de-emphasis, however, is that care must be taken when physically measuring the frequency response of a channel by using a constant level input signal not to overload the intermediate stages because of the high-frequency boost given by the pre-emphasis curve.

ii) Companding:

Companding refers to a technique for noise reduction of compressing the amplitude of the signal to reduce its dynamic range prior to transmission, and expanding the signal in a reverse manner at the receiving end. In the expansion process any noise accumulated during transmission is effectively reduced in inverse proportion to the audio signal level (i.e., a quasi-constant signal-to-noise ratio is maintained over a wide dynamic range). Two forms of companding are generally used. Instantaneous companding occurs when the instantaneous amplitude of the signal is subject to compression and expansion. Syllabic companding occurs when the envelope of the signal, averaged over a period of time, is compressed and expanded. Syllabic companding is now frequently employed on FM sound program circuits, but not on off-air broadcasts because it is not compatible with existing consumer equipment. An improvement in signal-to-noise ratio of 6 -10 dB for classical music and 8 - 14 dB for modern music has been claimed using Syllabic companding [11].

2.2.2 Digital

The use of digital encoding and transmission techniques is well established in the telephone industry and is progressively being used to a greater extent in the broadcast industry as well as being seriously considered for domestic hi-fi equipment. Two digital encoding schemes are in common use in the telephone industry and have been adapted for high-quality sound program transmission.

2.2.2.1 Pulse Code Modulation (PCM)

In this technique the analog waveform is sampled at a rate not less than twice the highest audio frequency present in the signal and converted to pulse amplitude modulation waveform (PAM). Each PAM sample is then encoded into an N-bit binary code word, depending on which of the possible 2^N quantized levels the pulse amplitude most nearly approximates. The choice of N determines the transmitted bit-rate and also the signal-to-noise ratio of the encoding process which is achievable over a given dynamic range of input signal level. This dynamic range can be extended by using instantaneous companding, which relies on the fact that PAM samples with high amplitudes may be encoded with less precision than small amplitudes, and the companding is achieved by using non-uniform quantization steps.

For telephony use, the standardised coding technique consists of 8 kHz sampling (to allow for a theoretical 4 kHz analog bandwidth) and 8-bit encoding giving a bit rate of 64 kbps. The use of companding provides a signal-to-noise ratio of more than 35 dB over a dynamic range of about 40 dB which is quite adequate for telephony. For a high-quality sound program circuit, however, a considerably wider bandwidth and higher signal-to-noise ratio will be required. No definite standards have been agreed as yet, but a sampling frequency of around 32 kHz is frequently used with 12 - 14 bits per sample leading to a gross bit rate of around 400 kbps.

This bit rate may be reduced somewhat by applying various forms of instantaneous or near instantaneous companding. For example, the DATE system [12] uses a sampling rate of 34.42 kHz (NTSC colour subcarrier frequency divided by 104) with initial 14-bit encoding, which is reduced to 12 bits by means of digital companding. A 13'th parity bit is added and four such channels are multiplexed together to give a total bit rate of 1.79 Mbps (i.e. 447.5 kbps per channel).

A system known as NICAM-3 [13] is being used by the BBC for sound program distribution. This uses 32 kHz sampling and initial coding with 14 bits, which is converted to 10 bits by near-instantaneous companding. The addition of various housekeeping bits leads to a bit rate of 338 kbps per channel.

2.2.2.2 Delta Modulation (DM)

Delta modulation is a form of digital coding in which the analog signal is sampled at a considerably higher rate than the Nyquist frequency, but rather than encode the resulting PAM waveform into N bits as in PCM, each sample is encoded as a 'one' or 'zero'. A 'one' indicates that the amplitude just sampled is higher than an integrated version of all the previous samples, a 'zero' indicates it is lower. Delta modulation can therefore be regarded as a one-bit version of differential pulse code modulation (DPCM) and the bit rate is equal to the sampling frequency.

As with PCM, the performance of the linear DM scheme described above can be improved by means of companding. Syllabic companding is usually applied and the result is known as adaptive delta modulation(ADM), since an algorithm is employed which adjusts the integrator step size to adapt to the syllabic nature of speech. One form of ADM is called CVSD or continuously variable slope delta, where the step size is adjusted in continuous uniform steps, whereas another form EVSD, or exponentially variable slope delta, adjusts in exponential steps. All of these techniques increase the dynamic range over which a given signal-to-noise ratio can be achieved.

For telephony, satisfactory communication quality can be achieved using a 32 kbps CVSD codec with a time constant of the order of tens of milliseconds. For high-quality program material, a much shorter time constant is used giving almost instantaneous companding. A subjective study for DOC by the University of Saskatchewan [14] using an EVSD codec has found that a bit rate of about 200 kbps gives audio quality comparable to off-air FM (equivalent to about 52 dB peak signal-to-weighted noise ratio). A bit rate of 400 kbps is approximately equivalent to 61 dB peak signal-to-weighted noise ratio. A custom LSI version of this high-quality sound program codec is under development [15].

2.2.2.3 Additional Practical Aspects of Digital Encoding

A comparison of the bit rates required to transmit high-quality audio using either pulse code or delta modulation, as described above, indicates that both coding schemes require a bit rate of the order of 300 to 400 kbps for high quality. One potential advantage of delta over pulse code modulation, however, is the performance under high bit error rates. This is well known for telephony applications where subjective tests [16] have shown that 48 kbps ADM at a bit error rate (BER) of 10^{-3} is equivalent to 48 kbps PCM at a BER of 10^{-5}. No information on the effects of bit errors on subjective performance is available for delta codecs at high bit rates, although the PCM coding techniques described in [12] and [13] are reported to perform satisfactorily at a BER of 10^{-5}.

A further potential advantage of delta modulation is that no framing is required, i.e. the incoming bit stream may be decoded directly without being re-arranged into N-bit words as for PCM. This not only implies simpler circuitry but means that any cycle slips occuring in the demodulator would not cause a loss of frame synchronization leading to a total loss of signal for several milliseconds while reframing occurs.

No information has been found on high quality sound program codecs using other than pulse code or delta modulation. On the other hand, there is considerable interest for

---

*Note that test tone-to-quantization noise ratio is directly proportional to rate for delta modulation, but increases exponentially with rate for PCM. For lower qualities, delta has the advantage of permitting a lower rate to achieve the same SNR. Hence 32 kbps companded delta and 64 kbps μlaw PCM provide the same subjective 4 kHz voice quality. In this application, however, delta does not enjoy a rate advantage. For a given rate PCM may in fact be preferred because it is less sensitive to high frequency content in the music (quantization noise increases with test tone frequency for delta, but is constant with test tone frequency for PCM).

telephony and military applications, in the use of adaptive differential pulse code modulation and delta-sigma modulation. It is conceivable that the application of such encoding schemes could be extended to high quality sound program distribution.

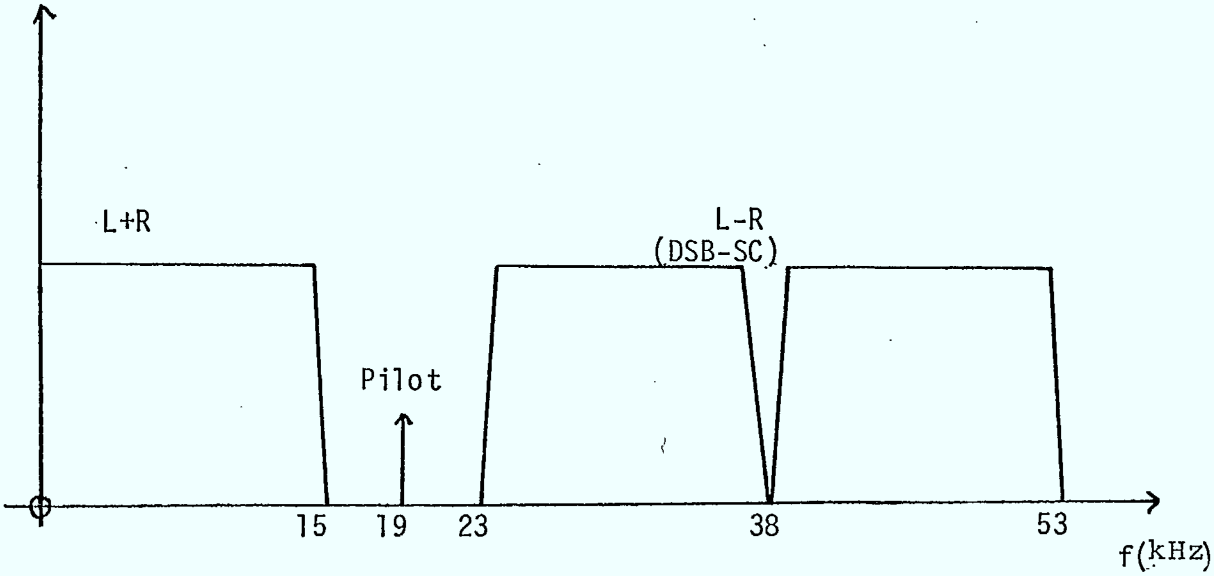
2.3 Analog and Digital Multiplexing Techniques

2.3.1 Analog

2.3.1.1 Conventional Stereo Broadcasting

One interesting and important example of analog multiplexing is in VHF-FM stereo broadcasting. In the initial design of VHF-FM stereo broadcasting it was mandatory that the stereo format would be compatible with existing monophonic receivers and the total RF spectrum occupancy would be no wider than a monophonic transmission. To achieve this aim the multiplexing format shown in Figure 2.1 is used. Left and right audio channels are summed into one composite baseband signal which provides a mono-compatible signal, while a signal formed from the difference of the left and right channels is used to amplitude modulate a suppressed 38 kHz subcarrier. A 19 kHz pilot (derived from the original 38 kHz subcarrier) is added to enable a synchronous demodulation to be carried out by the receiver. The main advantage of this scheme is that both left and right audio channels are carried via one RF carrier and the composite signal is mono-compatible. This is also a highly desirable characteristic for a direct broadcast satellite system.

The disadvantage, however, is that the signal-to-noise ratio for a stereo signal using this format is about 22 dB poorer [17] than for monophonic, for a given RF carrier-to-noise ratio. This arises for the following reason. In monophonic FM, only the noise in the range of the baseband



L+R deviation of main carrier ±35 kHz

L-R deviation of main carrier ±35 kHz

19KHz pilot deviation of main carrier ±5 kHz

FIGURE 2.1: BASED ON CHARACTERISTICS OF CONVENTIONAL FM STEREO SIGNAL

signal, i.e. up to 15 kHz is important, since higher frequency components can be filtered out. For stereo, the situation is different. Referring to Figure 2.1, the left minus right channel difference signal occupies twice the baseband bandwidth, and hence contributes a higher noise power. In addition, however, because of the parabolic output noise characteristic of an FM demodulator, there is already more noise in the range 23 to 53 kHz than 0 to 15 kHz. Pre-emphasis and de-emphasis partially offset the additional noise, but the overall effect is the 22 dB degradation of signal-to-noise ratio referred to above. This reduction in signal-to-noise ratio can be tolerated for commercial VHF-FM broadcasting since signal strengths are high anyway, but is a severe limitation of using this multiplexing technique for satellite applications.

2.3.1.2 TV Associated FM Sub-Carrier

A very common technique for transmitting sound with video is the use of a TV-associated FM subcarrier. This sub-carrier is located just above the spectrum of the video baseband signal. The composite signal may then be used to modulate an RF carrier. This system is used for conventional VHF and UHF TV broadcasting where the FM sound sub-carrier is located 4.5 MHz above the video carrier frequency (in the North American system).

For transmission of network video and audio by satellite, the composite baseband video and audio subcarrier is used to frequency modulate an RF carrier, and various options exist for placing the FM subcarrier. A typical format (from [18]) would be:

Audio sub-carrier frequency	6.8MHz
Peak deviation of audio sub-carrier	75kHz
Peak deviation of RF carrier by video	10.75 MHz
Peak deviation of RF carrier by audio	2 MHz

This leads to a total Carson's Rule bandwidth of 36 MHz, or one full transponder.

An obvious technique for providing additional sound circuits is to use more than one FM audio subcarrier. This method is particularly suited to domestic broadcasting as a means of obtaining either stereo TV sound or an additional audio channel in another language, which is compatible with existing domestic TV receivers. For example, a German system [14] uses an additional sound subcarrier at 5.742 MHz above the video carrier frequency in addition to the normal subcarrier at 5.5 MHz. The circuitry required to receive the additional carrier can be integrated on a single chip costing about $10.

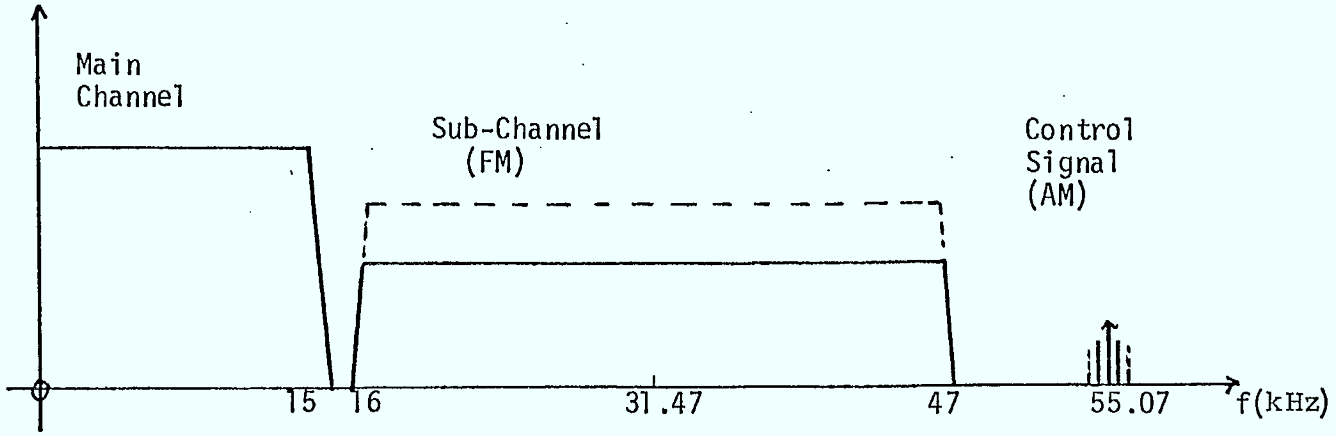
For transmission via satellite, where compatibility with broadcast TV format is not a requirement, there is more choice in the location of the additional subcarriers. Reference [20] describes a US system using two FM subcarriers at 5.8 and 6.4 MHz each carrying high-quality 15 kHz sound circuits. A further example is taken from [23], where 3 FM subcarriers at 5.14, 5.41 and 5.79 MHz were used, each carrying a 10 kHz sound program channel. The main problem with providing more and more subcarriers is the problem of intermodulation between the subcarriers and the video in the transponder, and this is the reason for choosing the subcarrier frequencies very carefully. This will be discussed more fully in Section 3.2. A practical upper limit seems to be about 5 subcarriers (i.e., 4 additional sound programs plus the video sound) in a scheme researched by CRC for DBS sound program distribution in Australia [22]. Each of the sound channels had 15 kHz bandwidth and provided a signal-to-noise ratio of about 55 dB.

An alternative method of providing multiple audio channels together with a video signal is to multiplex the separate audio signals together and frequency modulate a single sub-carrier. One example of this is an FM-FM multiplex system used in Japan to provide dual-channel audio for domestic broadcasting [23], [24].

As shown in Figure 2.2, in this scheme, the second channel frequency modulates a carrier at 31.47 kHz which is added to the first channel, and the composite signal then frequency modulates the TV sub-carrier. This provides a compatible signal for existing TV reception, but suffers from a reduced signal-to-noise ratio in the second audio channel.

2.3.1.3 Frequency Division Multiplexing

Frequency division multiplexing is a technique widely used in the telephone industry for transmitting multiple channels. In this method individual baseband channels are stacked in frequency as single-sideband suppressed carrier signals, each channel occupying the same bandwidth as the baseband modulating signal. The composite signal is then used to frequency modulate an RF carrier. One advantage of this method is that there is flexibility in the way in which program channels of different bandwidths can be combined, and a stereo signal is obtained by simply using two frequency slots. However, care must be taken not to exceed the multi-channel loading capability of the FM transmission system. A further disadvantage of this scheme for broadcast purposes is the cost associated with the demultiplexer filters and SSB demodulators, and potential crosstalk problems resulting from distortion of the FM carrier.



———————— Dual-sound Transmission

--------- Stereophonic Transmission

Main channel deviation of main carrier		±25 kHz
Sub-channel deviation of main carrier:	(i) stereo	±20 kHz
	(ii) dual-sound	±15 kHz
Control channel deviation of main carrier		±2 kHz
Subcarrier frequency		31.47 kHz(2 x f line)
Deviation of Subcarrier		±10 kHz
Control signal frequency		55.07 kHz(3 x f line)
Modulation frequency (AM):	(i) stereo	982.5 Hz
	(ii)dual sound	922.5 Hz

FIGURE 2.2: BASEBAND CHARACTERISTICS OF NHK TWO-CHANNEL TV SOUND SIGNAL

2.3.2 Digital

Once an audio signal has been digitized by either PCM or DM, several options are available for transmission. Several possibilities in current use are described below.

2.3.2.1 Time Division Multiplexing (TDM)

Several digitized bit streams can be multiplexed into one bit stream of a higher rate by interleaving the individual bit streams in time. For example, in the BBC NICAM-3 system referred to earlier, 6 sound channels of 338 kbps each are combined (along with framing and synchronizing bits) into a single bit stream of 2048 kbps. This is compatible with the so-called European 2 Mbps PCM systems for transmission over conventional digital lines. However, such a bit stream could also digitally modulate an RF carrier using PSK.

2.3.2.2 Sound in Sync

An attractive digital technique for combining TV audio with the video is to make use of the horizontal or vertical flyback intervals of the video signal. During these intervals it is possible to insert samples of the sound signal, which can be received at the receiver and demodulated. Several schemes using either the horizontal or vertical flyback interval are described in references [20] and [25]. Two high-quality 15 kHz channels can be made available using the horizontal flyback period.

2.3.2.3 TV Associated PSK Sub-carrier

This is a combination of digital modulation and the TV-associated subcarrier discussed in Section 2.3.1.2. In this scheme, however, the subcarrier is phase-shift-keyed by a digital bit stream consisting of one or more encoded audio channels. An example of this technique is DATE (Digital Audio for Television) referred to in Section 2.2.2.1 [12]. Four 15 kHz sound channels are sampled at 34.42 kHz and time division multiplexed to give a 1.79 Mbps bit stream. This bit stream digitally modulates a 5.5 MHz subcarrier using 4-phase PSK, which is combined with the video baseband signal and transmitted conventionally. A PSK demodulator is, of course, required at the receiver.

Additional work by the BBC [26] has shown, however, that while such a PSK subcarrier could replace a single FM subcarrier and provide at least 2 high quality sound channels, it could not be used in addition to the regular sound FM subcarrier without causing excessive disturbance to the video. Removal of the regular FM subcarrier would, of course, mean a loss of compatibility with domestic TV reception.

2.3.2.4 TV Plus Spread Spectrum Audio

One final technique worthy of mention for combining audio and video signals is the use of spread spectrum modulation of an audio channel on top of a conventional video channel. Such a scheme has been described [27], primarily for application in providing an additional digital data channel for the transmission of graphic and alpha-numeric data along with a standard video signal. This experimental system achieved a bit error rate of less than 2×10^{-5} at a bit rate of 100 kbps, and could no doubt be used to transmit a digitally encoded voice signal of reasonable quality.

2.4 User Interface Considerations

A major consideration in the choice of coding and multiplexing techniques which must not be overlooked is the impact on the users of the system. These users consist of subscribers who receive the signals and the broadcasters who originate them. Ideally, the choice of transmission format will be compatible with both.

2.4.1 Subscriber

The basic criteria which must be satisfied, as far as the subscriber is concerned, are that:

i) the cost of the antenna, low noise amplifier and down conversion/demodulation equipment should be as low as possible.

ii) the downconversion/demodulation equipment should provide outputs which are compatible with existing domestic equipment, i.e., VHF/UHF television receivers, VHF-FM tuners (mono or stereo) or stereo amplifiers.

On this basis, the use of digital sound encoding techniques leads naturally to the provision of a baseband audio output (left and right channels), for direct connection to an audio amplifier. However, selection of different programs would have to be made in the downconverter.

The use of FM (either as subcarrier or SCPC), on the other hand, could allow a direct translation of a spectrum of signals into the VHF FM band where an external UHF or stereo tuner could be used to make a program selection (see detailed discussion in 3.3.1.3). However, as discussed previously, the provision of high-quality stereo in this mode is difficult, due to the large reduction in signal to noise ratio when using the conventional stereo multiplex format.

A further consideration is the use of TV-associated sub-carriers or SCPC carriers*. This implies that only the radio programs associated with a particular video uplink can be accessed. This leads to problems if one member of a family wishes to listen to a radio program associated with a video signal different to the TV program which another family member is viewing.

2.4.2 Program Originator

Once again, the use of some form of digital coding requires that the baseband audio signal (left and right channels, if stereo) is available to the program originator. This may involve additional modulation/demodulation if the earth station is not physically close to the studios. TV plus sound channel multiplexing methods, of course, require that the program originator have access to the baseband video signal. In general, though, the interface requirements for the program originator should be of less importance than the user, since there will be considerably less program originators.

2.4.3 Flexibility and Growth Potential

As with any new scheme, a system for radio program distribution via satellite would not be expected to carry many channels at its inception. The system should, therefore, be designed to allow for future growth with an increase in in-orbit capacity. On this basis, the use of SCPC techniques provides the most flexibility for adding channels, (on the other hand augmenting the capacity of a single channel multiplexed digital radio program

---

*SCPC carrier frequencies are locked to that of the 14 GHz TV carrier, implying the TV associated AFC circuit in the DBS receiver also performs the necessary spectrum centering for the SCPC carriers.

distribution system would require extensive modification of the IF, baseband and probably downconversion subsystems to accomodate rate increases), as well as allowing uplink transmission from different locations.

From the subscriber's point of view, system growth should not require any re-arrangement or additions to the downconversion equipment. In this regard, a scheme which translates the radio programs into the VHF FM band, where they are selected by the subscriber would allow the greatest flexibility.

2.5 Digital Stereo Receiver

As mentioned previously, one disadvantage of FM/SCPC for a DBS system is that the provision of stereo using the conventional stereo multiplex format is not possible due to the large carrier-to-noise ratio required for a tolerable signal-to-noise ratio of the stereo signal. Nevertheless,the provision of stereo using a single RF carrier is a very desirable feature, and would lead to a fairly simple domestic receiving system since a downconversion could be made directly into the regular VHF FM broadcast band, for easier channel selection by the subscriber.

As discussed previously, one scheme which would provide high-quality stereo transmission is the use of digital encoding, time-division multiplexing of the individual channels and digital modulation of an RF carrier. In principle, it would again be very convenient to downconvert such a signal into the VHF-FM broadcast band, but in this case conventional FM demodulation would not work and some form of PSK demodulator would be required. This type of demodulation for conventional VHF broadcasting has, in fact, been suggested recently, [20], where Phillips are experimenting with an all-digital VHF broadcasting system. In other words, it is conceivable that future generations of domestic VHF receivers may have provision for PSK demodulation anyway. It is suggested that serious consideration be given to this approach as a long-term solution for radio program distribution. In the meantime, immediate future work would be carried out into the use of PSK in the conventional VHF/FM broadcast band.

3.0 CANDIDATE RF TRANSMISSION TECHNIQUES

This section briefly examines various transponder access techniques which might conceivably be used for radio program distribution in a DBS scenario. Although some techniques might not be desirable from the standpoint of power/bandwidth requirements and/or radio receiver complexity, these have nevertheless been included for the purposes of discussion in accordance with the stated objectives for Phase 1 of the study. Since all these multiple access techniques have been amply covered in the literature and are, no doubt, quite familiar to the reader, discussions will be focussed towards the application of these techniques strictly for the distribution of radio programming.

3.1 Baseband/IF Interface

The interface between the baseband and the RF subsystems, for the purposes of these discussions, may be defined as being the input to the IF modulator (FM or PSK) on the transmit side and the output of the RF or IF demodulator (FM or PSK) on the receive side.

Before proceeding, however, with the discussion on transponder access techniques, it is necessary to pair the mode of the baseband signal, which might be either analog or digital, with the appropriate modulation/access technique(s) in order to confine the number of possible combinations to those which are realizable.

Table 3.1 summarizes realizeable combinations in matrix form which are discussed further below.

	TRANSPONDER ACCESS TECHNIQUE						
BASEBAND SIGNAL	FM TV	FM SCPC	FDM/FM/FDMA	DIGITAL SCPC	TDM/PSK/FDMA	TDM/PSK/TDMA	SSMA
FM Subcarrier(s)	X		X				
Analog Audio Channel		X					
FDM Audio Channels			X				
Digital Audio Channel				X			X
TDM Audio Channels					X	X	X

TABLE 3.1 CANDIDATE RADIO PROGRAM TRANSMISSION TECHNIQUES

3.2 FM/TV Subcarrier(s)

This technique for television-associated sound program distribution utilizes audio subcarrier(s) located above the video baseband and is a well known mode of transmission used by such agencies as Telesat Canada [7] and INTELSAT[8]. The ramifications of also employing this mode of distribution for radio programming are discussed below.

3.2.1 Power/Bandwidth Considerations

Transmitting the radio programs via a small number of TV subcarriers results in a minimal loss of effective satellite power since the transponder is typically operated at saturation, in the case of single access FM per transponder. Since the net deviation of the main RF carrier can reasonably be assumed to be due to the root-sum-square (RSS) summation [18], [28], [29] of the deviations due to the video baseband signal itself and the various TV subcarriers, it is clear that for a given transponder bandwidth allocation, as the number of TV subcarriers increases, the RF deviation due to the video signal must be reduced to maintain a fixed composite rms deviation (some reduction in composite deviation may in fact be required to ensure acceptable IM distortion with increasing subcarrier frequency). The fact that some minimum RF deviation due to the video baseband is essential to meet video SNR requirements implies that the number of TV subcarriers which can be supported is limited. In general this technique is not conducive to expansion of radio program capacity.

This situation is even more acute for the case of multiple (two or possibly three) TV carriers per transponder in which overall FM deviation is reduced and the parasitic effect of the subcarriers on video performance becomes more severe. In this case, depending on the DBS system parameters and performance requirements, TV subcarrier capability could conceivably be limited to a single subcarrier sufficient only for the transmission of TV-associated sound program.

3.2.2 Intra-System Interference Considerations

For the TV subcarrier method of radio program distribution, the interference which will be of major concern will be due to intermodulation products falling on the subcarriers themselves or within the video baseband formed as a result of distortion of the FM RF carrier caused by non-linearities and band-limiting filters. One such device whose linearity will be of prime concern is the FM discriminator itself. Minimization of the impact of IM interference will thus be dependent on ensuring adequate linearity of transmission devices and the proper selection of operating parameters.

3.2.3 External Interference Considerations

The radio program signal(s) will be no more sensitive than the video to most forms of RF interference. One notable exception is a (potentially) narrowband interferer offset from the video carrier by approximately the sub-carrier frequency, which under certain video modulation conditions can be demodulated as a narrowband interferer to the sub-carrier.

3.2.4 Incremental DBS Equipment Requirements

There is no incremental receiver RF front end hardware that will be required for this method of radio program distribution although some equipment (filters, mixer/LO, etc.) will be required to extract the radio program subcarriers from the composite video baseband for direct frequency translation into the FM broadcast band (in the case of monophonic FM). In the case of stereophonic programs, demodulation of the relevant sound subcarriers (two required) will be required to derive the left and right audio channel for either direct inputting to the user's stereo amplifier system or for subsequent remodulation into the FM stereophonic broadcast format and insertion into the FM broadcast band from which a tuner may then be used to extract the relevant carrier(s). Remodulation is probably quite unnecessary for direct-to-home service since it seems reasonable to assume that if a user can afford a DBS receiver then the probability is quite high that he will either already possess or could readily afford to purchase a stereo system with external baseband input jacks.

In terms of cost impact and technical complexity, the TV subcarrier approach is expected to have the least incremental cost impact and technical complexity when compared to the other distribution techniques discussed later. Both cost and complexity will be of prime concern in a direct-to-home DBS service scenario.

3.2.5 Flexibility and Growth Potential

Distribution of radio programs via the TV subcarrier technique is limited both in terms of growth and in terms of flexibility, in both cases because of intimate coupling with the video signal. In the latter case, it is clear that all radio program channels must originate from a single transmission point which is also the source of the TV signal. Whether or not this lack of flexibility can be considered as an unacceptable drawback will be determined by the assumed service scenario, bearing in mind that this lack of flexibility minimizes the incremental cost impact and equipment complexity in the DBS receiver.

The lack of growth potential is perhaps a more negative feature of this approach which can only be overcome by resorting to other transmission techniques (e.g. SCPC, FDM/FM,etc.) in which the radio program system is constrained only by satellite transponder power and bandwidth allocated to it.

3.3 SCPC

SCPC has been used for radio program broadcasting under essentially two different scenarios:

1) A small number (<5) of SCPC carriers sharing the transponder with a TV carrier and,

2) A large number (>5) of SCPC carriers possibly sharing the transponder with other FDMA carriers (including TV).

An example of the former is the approach adopted by Telesat Canada in transmitting a radio program carrier 16 MHz below the video carrier in the TV transponder [30]; examples of the latter include the system implemented on Western Union's Westar satellite for National Public Radio [31], [32] and the Algerian DOMSAT system.

3.3.1 Shared Transponder - TV Plus Small Number (<5) of Radio Program SCPC Carriers

3.3.1.1 Power/Bandwidth Considerations

The placement of a small number of radio program SCPC carriers at the edge of band in a TV transponder requires careful selection of uplink EIRP's and radio program carrier frequencies and bandwidths in order to minimize video degradation while still meeting radio program performance requirements.

Figure 3.1 illustrates the configuration utilized by Telesat on the Anik B satellite for CBC 5 kHz radio program distribution over a saturated TV transponder.

Note that the 20 dB downlink power difference shown in Figure 3.1 implies an uplink power difference of only about 15 dB due to nonlinear suppression through a nearly hard limiter [43]. Furthermore both the video and SCPC carriers experience the "large signal" gain of the transponder, which is 5 dB less than in the linear region of operation (see Figure 3.1a). This implies that up to 10 dB more radio program carrier uplink EIRP is required to produce the same downlink EIRP compared to operation in a backed-off (e.g., Thin Route) transponder. In fact, a further uplink EIRP as well as transponder utilization penalty may be imposed by the need to compensate the effective reduction in downlink carrier amplitude caused by destructive addition of the "multipath" signal admitted to and radiated from the adjacent transponder [44]. Such multipath effects will however be minimal if adjacent transponders illuminate different spot beams.

Note that the additional uplink EIRP per radio program carrier required to operate within the TV transponder may have impact on the economy of shared versus dedicated transponder operation, depending on the number of transmitters in the system.

3.3.1.2 Interference Considerations

The design of a shared (TV plus radio program carrier) transponder arrangement must consider the following effects:

i) direct interference between the two carriers*:

---

*In the Telesat system both fall within the other's receive noise bandwidth - this was necessitated by the desire not to replace TV transmit and receive equipment.

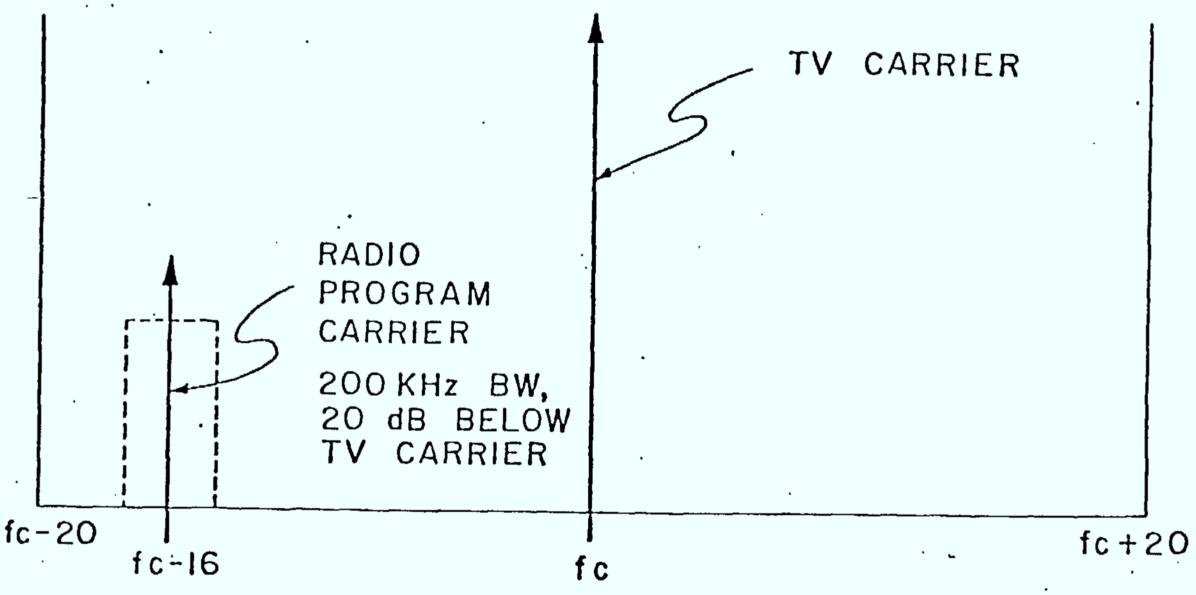


FIGURE 3.1 RADIO PROGRAM AND TV CARRIER WITHIN AN ANIK TRANSPONDER

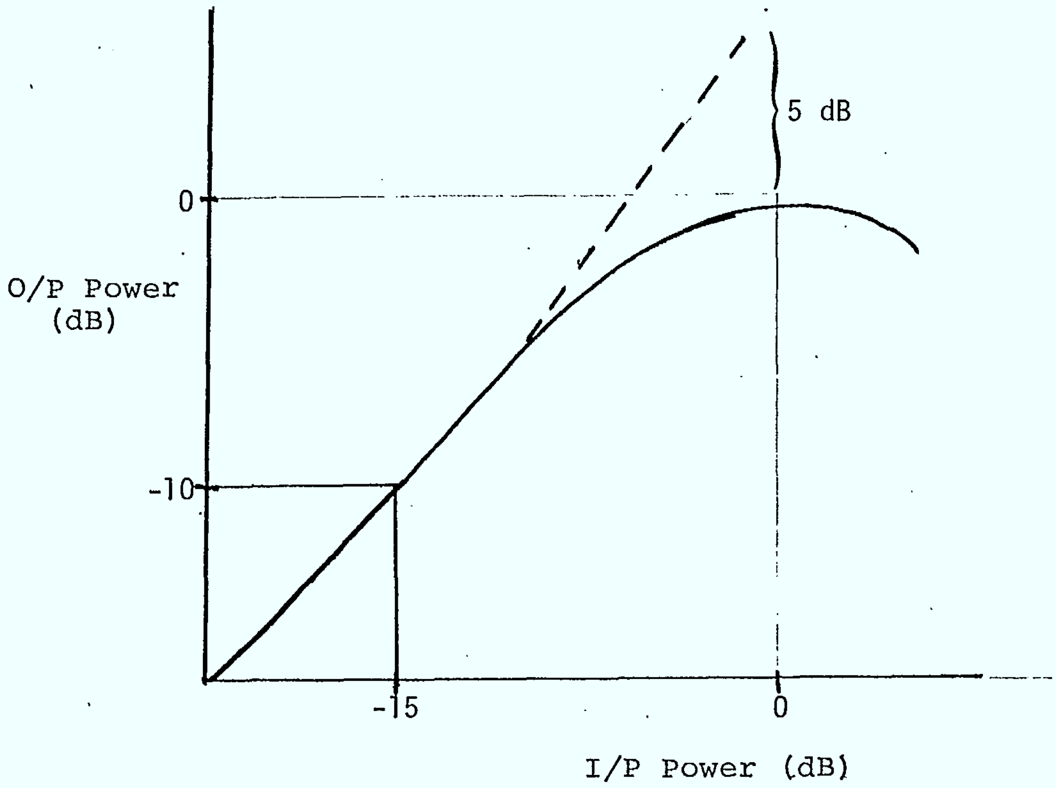


Figure 3.la Transponder Gain Characteristic

(ii) nonlinear suppression of the radio program carrier by video carrier;

(iii) the leaking of the radio program signal through the lower adjacent channel multiplex filter and subsequent amplification at up to 10 dB more gain as discussed, resulting in slow amplitude modulation with the sympathetic and destructive addition of the principal and multipath components [44] (the extent to which the radio program carrier can be pushed to the edge of an Anik A passband is limited by multipath);

(iv) the generation of a large 2A-B product comparable in size to the radio program carrier but of much wider bandwidth appearing on the far side of the transponder and interfering with both the TV carrier and adjacent transponder traffic.

In the case of multiple radio program carriers, to avoid comparably sized $2f_v - f_r$ (f_v = video carrier frequency, f_r = radio program carrier frequency) IM product(s) falling in the vicinity of the radio program carriers, these will all have to be grouped on one side or the other of the transponder. Then, as illustrated in Figure 3.2, the unwanted products will be centered on the far side of the TV carrier well away from the program carriers. The program carriers will then be subject only to the low-level IM products generated among themselves which will be acceptable in level and/or avoidable with frequency planning - see 3.3.2.1.

The addition of one radio program carrier falling within the noise bandwdith of a TV receiver will degrade TV threshold performance because of power sharing, direct interference, and 2A-B product interference. Since the interferers to the TV carrier are all well separated in

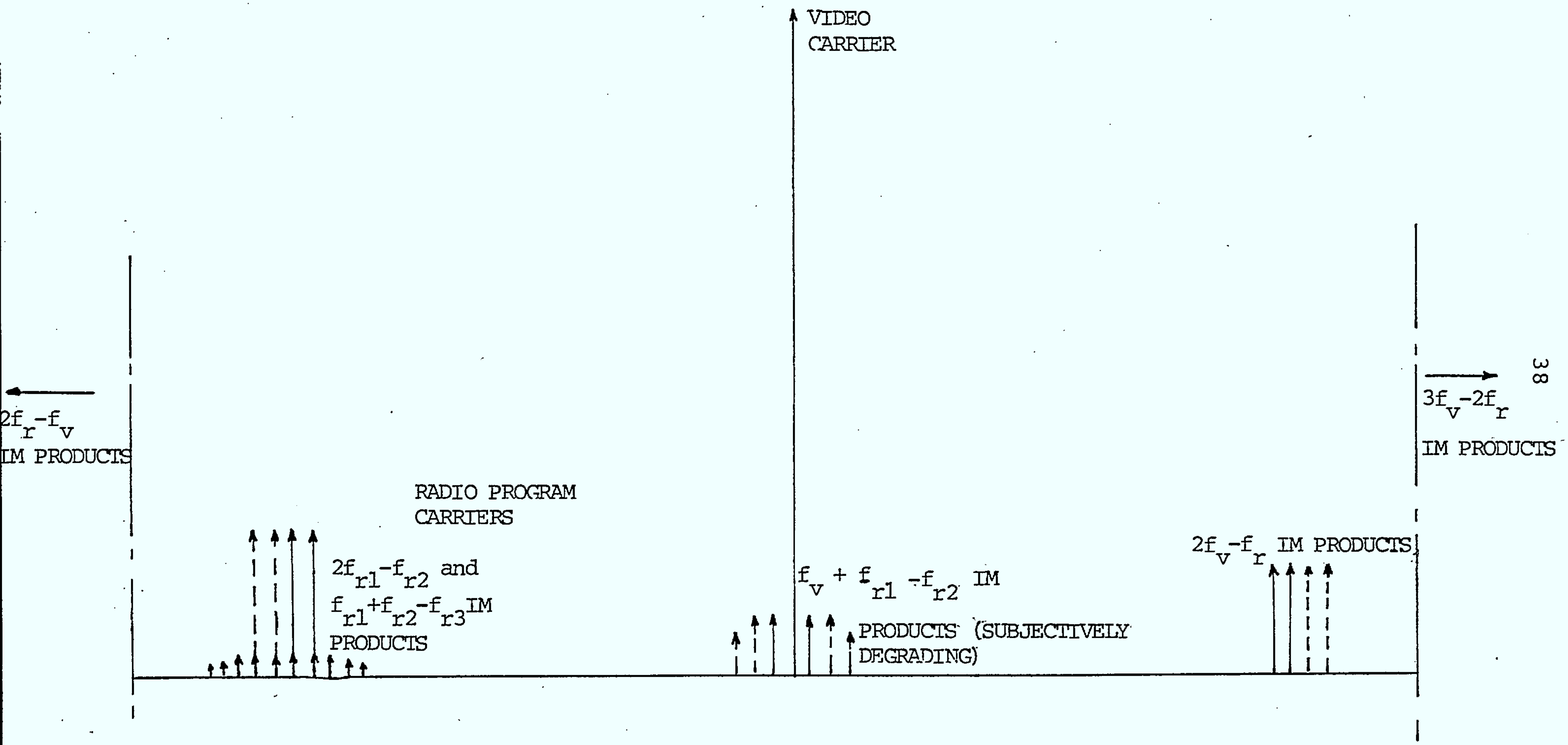


FIGURE 3.2 MULTIPLE RADIO PROGRAM FM/SCPC CARRIERS AND TV CARRIER WITHIN AN RF CHANNEL

frequency, however, their effect on weighted video SNR above threshold will be small. Depending on margins assigned to the 12 GHz downlink, performance in the vicinity of threshold may, however, assume considerable importance.

More serious problems are encountered when we attempt to add a second "parasitic" radio program carrier to a transponder carrying video. This was demonstrated in an analysis performed by MCS for CBC [7] and confirmed in subsequent tests performed by Telesat.

A second radio program carrier will cause $f_v + f_{r1} - f_{r2}$ and $f_v + f_{r2} - f_{r1}$ 3'rd order products to fall $\pm\Delta f_r$ (Δf_r = separation between radio program carriers) away from the TV carrier centre frequency. Although these products are about 18 dB below the $2f_v - f_r$ products and spread over the entire transponder bandwidth, because they are modulated in the positive sense by the TV signal, they will be demodulated as narrow band interferers centred at Δf_r MHz. Since $\Delta f_r < 1$ MHz typically, essentially no FM or noise weighting advantage will apply to these interferers, and despite their low level they must be reckoned with in computing video SNR. Of even greater significance for direct broadcast (as opposed to network quality transmission) applications is the fact that this interference is subjectively perceptable above threshold when up to 5 radio program carriers are present [45].

As subjectively perceptible interference is generally unacceptable for any video service, the only solution to this problem is to substantially back off the TV carrier and accept a significant loss in satellite power utilization efficiency.

3.3.2 Dedicated Transponder or Larger Number (>5) of Radio Program Carriers Sharing TV Transponder

This mode of radio program transmission assumes that the SCPC carriers either solely occupy the transponder or share it with other non-saturating FDMA carriers (possibly one TV carrier). It is also assumed that sufficient bandwidth is available to accomodate system growth.

In the case of TV plus SCPC radio program carriers, separated from the video carrier by a guardband at least equalling the composite SCPC bandwidth, note that no potentially narrowband and relatively high level IM products due to the video carrier will fall in the SCPC band. This sharing arrangement, illustrated in Figure 3.3, allows the transponder to be operated near saturation (for a sufficiently large number of SCPC carriers the previously discussed $f_v + f_{r1} - f_{r2}$ products do not subjectively degrade the video). Such a system is described in [40] and was also the subject of a study undertaken by Dr. R. G. Lyons on behalf of Telesat in 1975 for Western Union Telegraph Co.

3.3.2.1 FM/SCPC Power/Bandwidth Considerations

One of the prime concerns in SCPC transmissions is the need to minimize the level of the in-band third order intermodulation products of the form 2A-B and A+B+C, the latter being 6dB higher than the former, generated by multicarrier amplification in the nonlinear satellite TWTA. This is usually achieved by operating the transponder in a backed-off mode (~5 dB multicarrier output backoff), i.e., operating in the linear (small signal) region of the TWTA power transfer curve. This allows carrier frequencies to be equally spaced, but has a detrimental effect on the available downlink EIRP [46]. The output backoff required, however, can be minimized if carrier frequencies

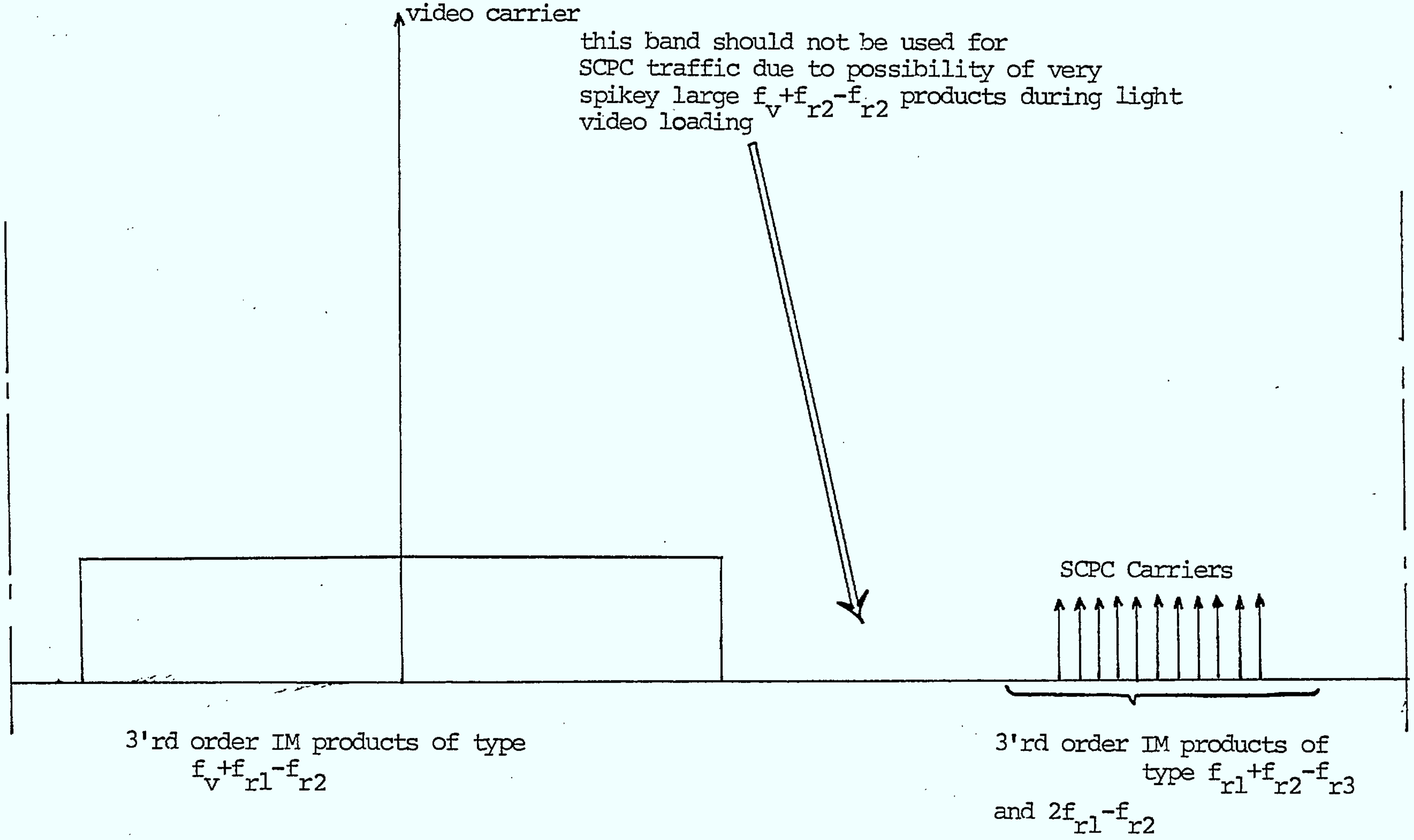


FIGURE 3.3 TV PLUS LARGE NUMBER OF SCPC CARRIERS TRANSPONDER SHARING ARRANGEMENT

are judiciously chosen such as to avoid channels in which third IM products are present. The application of this technique implies, however, the availability of ample bandwidth and the tolerable presence of a significant number of unused channels. Fang and Sandrin [35] have determined optimum (i.e. minumum bandwidth) assignments for up to 11 carriers; beyond this number, only suboptimum assignments can be realized.

Assuming, for example, a channel spacing of 200 kHz in order to arbitrarily conform with that used for the FM broadcast band, for 11 radio program channels, the number of consecutive channels required for an optimum assignment would be 73, i.e., a total bandwidth of 73 x 0.2 = 14.6 MHz. For a maximum of 20 radio program chnnels (monophonic) a suboptimum assignment would require 284 consecutive channels or a bandwidth of 56.8 MHz. A tradeoff thus exists between maximizing the available downlink EIRP per carrier versus maximizing the use of the transponder bandwidth.

The second power/bandwidth tradeoff associated with FM is the selection of deviation and channel spacing. In a power limited system the link is generally designed to operate just above (i.e. with appropriate fade margin) threshold, to derive the greatest FM S/N advantage. Note that the FM stereo receiver compatible deviation and spacing parameters does give up about 1 dB in possible FM advantage (i.e. 1 dB higher C/N is required to obtain same audio S/N - see Chapter 5, Figure 5.1).

3.3.3 Additional Power/Bandwidth Considerations for Digital SCPC

In the case of digital SCPC, the choice of modulation greatly affects not only the power/bandwidth considerations but also the complexity, and hence cost, of the receiver (downconverter including AFC system as well as demodulator). In this context, the two modulation schemes which are probably most noteworthy are 2-phase differential PSK (DPSK) and 4-phase coherent PSK (QPSK), the latter of which is commonly used in satellite Fixed Service applications. MSK (with coherent integrated and dump detection), which has the same theoretical E_b/N_o performance and a slight bandwidth penalty compared to QPSK, is an alternative to QPSK which reduces demodulator complexity and also increases tolerance to phase noise [42, 43].

While 2-phase DPSK is half as efficient as QPSK in terms of bandwidth usage, and requires about +0.5 dB more E_b/N_o at a BER = 10^{-5} when compared to differentially-encoded (for ambiguity resolution) coherent PSK, DPSK is recommended because the demodulator is both simpler to implement and far less susceptible to phase noise on the received carrier. If bandwidth is at a premium differential detection of MSK [47], which gives the same E_b/N_o performance as DPSK, but requires a slightly more complex modulator and demodulator, is recommended.

In digital SCPC, the digital bit stream from PCM or delta encoder is typically used to phase shift key an IF carrier. For high-quality audio, the source rate (DM or PCM encoded) will be approximately 300 - 400 kbps (reference 2.2.2.3) and assuming 2-phase DPSK, the RF bandwidth required will be about 480 kHz. Allowing about 10% for guardbands, the allocated RF bandwidth thus required would be in the vicinity of 530 kHz.

3.3.4 External Interference Considerations

For the DBS receiver, downlink interference from co-channel (co-polarized and cross-polarized) transponders on adjacent satellites and adjacent channel interference (ACI) will be of paramount importance.

Adjacent satellite interference is of particular concern because both antenna gain discrimination and wanted received radio program carrier level will be relatively small.

The extent of this corruption will depend on the modulation of the SCPC carrier and the type of interfering co-channel carrier, as well as on the average carrier-to-interference ratio. There are basically three categories of interference:

(1) Stationary wideband interference

(2) Stationary narrowband interference

(3) Non-stationary interference

For <u>stationary wideband interference</u>, the interfering carrier has a much wider bandwidth than the radio program SCPC carrier bandwidth and its effect is therefore equivalent to that of thermal noise*.

The following types of interfering traffic fall into the wideband category:

- FDM/FM/FDMA (with energy dispersal present during light loading)

---

*A sufficiently narrow bandwidth of a stationary random process is asymptotically Gaussian.

- Single carrier FDM/FM (e.g. 960 channel message)
- PSK/TDMA (scramblers are normally used to ensure random bit patterns)

FM/TV interference is not included in this category because it possesses some non-stationary characteristics as well as harmonic components.

For stationary narrowband interference, the interfering carrier bandwidth apoproaches the SCPC carrier bandwidth and the interference at the SCPC demodulator input is neither white nor Gaussian. A detailed treatment of narrowband interference on FM/SCPC and DM/PSK/SCPC is contained in [36].

Narrowband interferers into SCPC systems include:

- low-capacity FDM/FM/FDMA carriers possessing no energy dispersal
- SCPC and radio program carriers
- RF harmonic components of a TV/FM carrier possessing no energy dispersal
- other narrowband traffic

For our purposes, non-stationary interference can be defined as interference which produces variations in performance at the output of the SCPC demodulator.

Because they are relatively narrowband and low power, FM (and digital) SCPC carriers will be vulnerable to various types of non-stationary interference that could be generated in a satellite system. Among these are:

1) Slow, periodically time-varying RF spectral components of a TV carrier.

2) A TV carrier modulated only with slow sweep (30 Hz) energy dispersal*.

3) On/off initial acquisition ranging tone(s) in a TDMA system.

4) Components of TDMA carrier at the burst repetition frequency.

5) Swept frequency carrier generated by a link analyzer.

All of these processes will vary at a rate less than the bandwidth of the radio program SCPC carrier and will, therefore, produce transient or time-varying effects not predictable by quasi-stationary analysis. The average carrier-to-interference ratio may be high but the subjective effect significant.

It is important to note one distinct difference between the effect of interference with FM/SCPC and digital SCPC systems: RF interference in a digital transmission system is not demodulated directly into baseband interference, but rather increases the bit error rate which decreases the signal to noise ratio of the audio channel. When the

---

*Energy dispersal of TV carriers may not be required at 12/14 GHz since there is presently no CCIR restriction on EIRP at this frequency band to protect low modulation index multi-channel terrestrial FM systems.

system is operating well above threshold (i.e. under fair weather conditions), this increase in bit error rate may have a very minor effect. A digital SCPC system is, therefore, less sensitive, in general, than an FM/SCPC system to narrowband interference for the following reasons:

1. The effects of interference can be completely compensated by an increase in the carrier-to-thermal noise ratio. Due to its peak-limited nature, the degradation due to angle modulated carrier interference is normally less than that of an equivalent power of thermal noise.

2. Unlike FM, no subjective degradation due to modulation on the interfering carrier will occur.

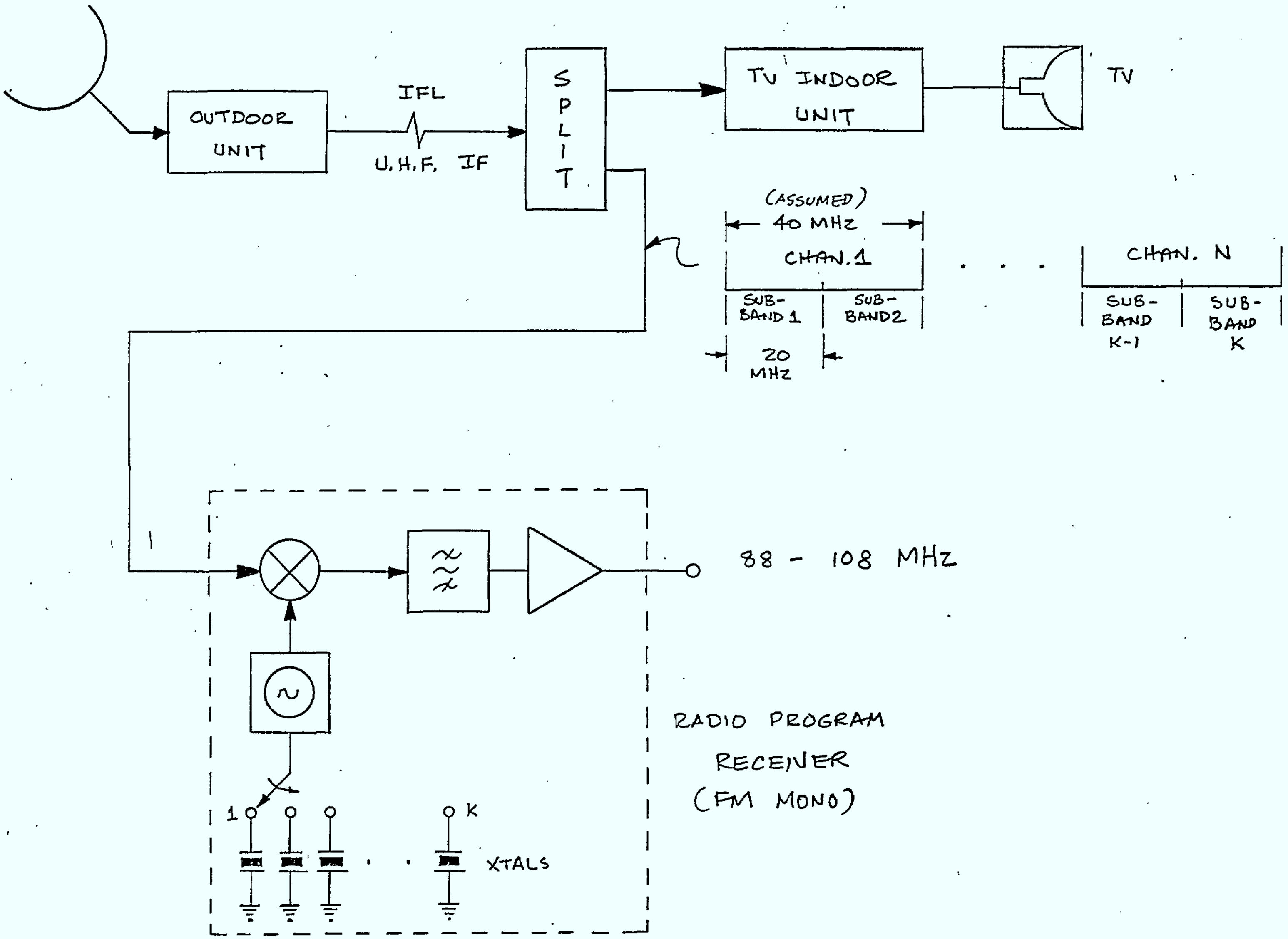
3.3.5 Incremental DBS Equipment Requirements

Using SCPC, the incremental hardware required for receiving sound program carriers along with TV could be relatively uncomplicated, although certain equipment performance parameters are more stringent for sound program. These parameters will be discussed in more detail below.

An example of a possible TVRO is shown in Figure 3.4. The incoming signals from the antenna (in this case 11.5 to 12.0 GHz) are amplified by the low noise amplifier, LNA, and mixed with a fixed tuned local oscillator, LO, to give a tunable IF from 900 MHz to 1.4 GHz. A second, tunable, local oscillator is then used to select the individual TV signal from the 500 MHz spectrum and convert it to a fixed IF of 70 MHz. Conventional demodulation of the video and audio sub-carrier is then carried out.

Note that if the SCPC carriers are sharing the same transponder with the TV, it is possible to share the second downconverter to provide simultaneous TV and radio program reception.

FIGURE 3.4 RADIO PROGRAM FM/SCPC RECEIVER



In this case, the TV AFC is applied to the second local oscillator, to account for drift in itself and the drift of the first fixed tuned local oscillator (which could be several hundred kHz). It should be noted, however, that this drift can be tolerated because of the wide (18 MHz) bandwidth of the video carrier.

In principle, several possibilities exist for adapting this receiver structure for radio program reception. Firstly, it is assumed that the radio program carriers are in the 12 GHz band, and hence no changes are needed in the antenna and LNA. (It is assumed that no change in G/T is required.)

Requirements on frequency uncertainty and phase noise at the demodulator are more stringent for radio program than TV because of the much narrower bandwidths involved. The normal solution in SCPC systems is to use a system pilot to perform an "instantaneous" correction, but this adds extra complexity to the receiver [42].

An alternative method of reducing frequency uncertainty is to apply the spectrum centering AFC loop for the TV carrier to the radio program carrier at UHF as shown in Figure 3.5. (It is not usually practical to apply AFC to the first local oscillator). However, because of acquisition problems, AFC at the second local oscillator can only correct for a limited amount of drift of the first oscillator, and ideally the frequency uncertainty of the first oscillator should be less than half the bandwidth of the radio program carrier (i.e. no more than ±100 kHz).

This still leaves the problem of oscillator phase noise. This phase noise is transferred to the received signal during the mixing process, and causes a different subjective effect depending on whether the carrier is analog FM or digitally modulated.

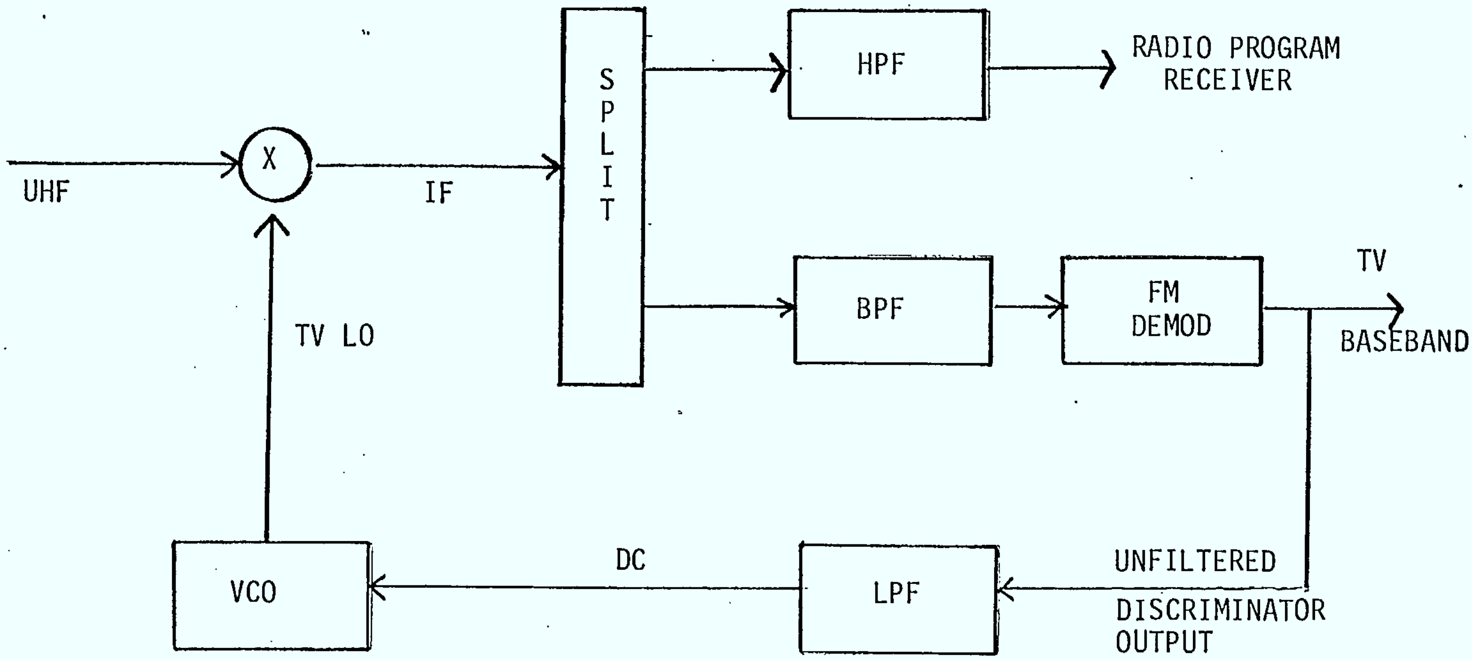


FIGURE 3.5 AFC ARRANGEMENT FOR SCPC RADIO PROGRAM RECEIVER

With FM/SCPC, the phase noise is demodulated directly into baseband, appearing as unwanted noise with predominant low frequency components. With digital SCPC, phase noise causes an additional reduction of E_b/N_o at the PSK demodulator, leading to an increased BER, and an increase in the overall noise level of the baseband signal. Note that in binary DPSK or DMSK (see 3.3.3) it is the phase noise induced phase change over one symbol period of delay (i.e caused by phase noise components beyond ±symbol rate from the carrier) that produces such a degradation, whereas in CPSK it is the phase change over the (carrier recovery circuit bandwidth)$^{-1}$, which is typically one to two orders of magnitude greater. Note also that in the binary PSK case the degradation is only 10 log $(\cos^2\varepsilon)$ (ε=phase error), compared to approximately 10 $\log(\cos^2\varepsilon/1+ E_b/N_o \sin^2\varepsilon)$ for QPSK or MSK.

Returning to the radio program receiver we assume that a frequency conversion takes place to an IF of 900 to 1400 MHz, where the signal is split off to go to the radio program demodulator as shown in Figure 3.4. At this point several alternatives exist:

(a) A second local oscillator, switchable if necessary in 20 MHz steps, can be used to give a block translation down to the VHF/FM band of 88-108 MHz. A conventional VHF/FM receiver operating as a tunable second IF is then used to select individual stations. This has the advantage of simplicity and ease of operation, but has the following constraints: -

  (i) The deviation and pre-emphasis of the transmitted signal must be compatible with conventional FM broadcasting.

(ii) Channel spacing must be the same as conventional FM broadcasting (200 kHz),

(iii) Channels coincident with local VHF/FM broadcast frequencies will be subject to interference.

(iv) For obvious reasons this technique is not suitable for digitally modulated SCPC.

(v) For the reasons given in 2.3.1.1, only monophonic programs could be received.

(vi) AFC in addition to that obtainable using the TV carrier (see Figure 3.5) could only be applied using the pilot tone method, since no one signal appears at the output to lock on to.

(b) A variation of the above is to provide a second local oscillator switchable in steps equal to the channel spacing, to give a fixed IF output in the VHF/FM band. Program selection is thus made external to the FM receiver, in a similar manner to selecting stations with cable TV converters.

The remarks made above in (i), (ii), (v) apply also, but one important advantage is that AFC could be performed in the converter using a discriminator rather than a pilot tone since a single signal appears at the output.

(c) An alternative to making use of a conventional VHF/FM broadcast receiver, is to provide demodulation right down to baseband audio in the unit itself. This has the advantage of not requiring broadcast standard FM deviation, pre-emphasis, channel spacing etc. and, of course, is the only method of demodulating digital SCPC.

(d) Reception of stereo would be possible by tuning to two separate carriers, in the case of FM, or a single digital carrier modulated with left and right multiplexed channels. Note that in both cases, the flexibility exists to remodulate the baseband audio signals (either mono or stereo) back into the conventional broadcast format to feed a VHF/FM receiver.

3.3.6 Flexibility and Growth Potential

The insertion of radio program carrier(s) at the edge of the TV transponder provides the inherent flexibility associated with SCPC, namely:

1. the radio program transmission system can be designed more independently of the TV transmission system than in the TV subcarrier case (e.g. radio program material need not originate from the same point as the video),
2. radio program slot(s) may be accessed by any originating center,
3. DBS receivers need not be constrained to receive television in order to receive radio program carriers (as in the case of the TV subcarrier technique),

However, this technique for radio program broadcasting is nevertheless constrained both in terms of where the SCPC carrier(s) may be placed relative to a near saturating video carrier in order to avoid mutual interference and in the number of such carriers which can be accommodated, i.e., system growth may be limited by factors such as power sharing, bandwidth sharing, IM interference, and multipath (note [44] that multipath is more severe when the transponder is saturated due to the gain compression applied to the wanted component).

The carrier-to-noise density (C/N_o) requirements for PSK/SCPC and FM/SCPC are comparable for peak signal-to-weighted noise ratios in the region of 50 dB. For higher SNR's (e.g. 60 dB) the C/N_o required for PSK/SCPC will be considerably less than that for FM/SCPC [38]. Both have sharp threshold characteristics under degraded C/N_o conditions, which may have implications on edge of beam coverage capability.

3.4 SSB/FDM/FM/FDMA

3.4.1 Power/Bandwidth Considerations

Radio program channels are frequency division multiplexed (using single sideband techniques) into a composite baseband which FM modulates an IF carrier. If the resultant FDM/FM carrier then accesses a DBS transponder in single carrier mode or shares it with a video or second FDM carrier, there will be little if any backoff or bandwidth penalty as is the case with the SCPC option.

It has been determined that a program channel presents a much higher average loading to a multiplex network, owing to the more frequent presence of sustained high level commentary and music on such a channel, that is approximately equivalent to 8 voice channels. SSB multiplex equipment exists for multiplexing four 15 kHz program channels into the equivalent format for 24 voice channels [37]. For 10 monophonic 15 kHz program channels, the equivalent voice channel loading would therefore be approximately 60 voice channels and the RF bandwidth required would be in the order of 4.5 MHz. For a transponder with a usable RF bandwidth of 18 MHz (say), three such FDM/FM carriers (i.e., a radio program channel capacity of 30 channels) could be accommodated in an optimum manner [9], i.e., free of third order IM products, by placing the carriers at -6.75, -2.25 and +6.75 MHz respectively, relative to the center of the transponder. Alternatively, a single FDM/FM carrier in an 18 MHz bandwidth would accommodate about 75 monophonic 15 kHz program channels.

For stereo program channels, two SSB program channels are typically used with a total loading equivalent to approximately 32 voice channels. Thus, approximately 30 stereo program channels could be accommodated on a single FDM/FM carrier (equivalent to a 960 channel message carrier) accessing the transponder. Further capacity could be obtained by reducing the peak loading and dynamic range of the stereo channels through the use of program companders.

In addition, FDM/FM systems are sensitive to crosstalk from high level sound program(s) into a quiet channel(s). This is caused by distortion or truncation of the RF spectrum (for FM SCPC this results in audio distortion at high signal level only). To avoid crosstalk for a small number of radio channels of large dynamic range requires the use of a high FM peak factor, which reduces power/bandwidth utilization efficiency (see Appendix A, Section A.6). Individual channel companding to reduce the subjective effect of crosstalk and the peak-to-rms of the composite signal may be necessary to improve transmission efficiency.

In the FDM/FM approach, a key requirement will be to ensure that the SNR of the highest program channel in the FDM baseband meets the minimum SNR requirements. Pre-emphasis/ de-emphasis may thus be required as in ordinary message FDM/FM.

3.4.2 Intra-System Interference Considerations

By multiplexing the program channels using SSB techniques, IM interference associated with multicarrier transponder operation (e.g., SCPC/FDMA) is circumvented and optimum use of transponder power can be realized by operating the transponder closer to saturation.

3.4.3 External Interference Considerations

With respect to adjacent satellite and adjacent transponder interference, a low capacity (or lightly loaded) program channel FDM/FM carrier will experience the greatest interference from a similar co-channel FM carrier. However, due to its higher power level, the FDM/FM carrier will normally be less prone to interference than an SCPC carrier.

3.4.4 Incremental DBS Equipment Requirements

Adoption of the FDM/FM approach to radio program distribution will require fairly substantial equipment retrofit to implement a radio receiver that will basically be identical to a message FDM/FM receive subsystem. Since the performance of the DBS station will be determined by the operational requirements for television, it must be ensured that the C/N_o requirement for the FDM/FM carrier needed to achieve the minimum SNR performance in the top baseband program channel is also satisfied.

The radio program receiver will basically consist of a downconverter to translate the UHF output of the DBS Outdoor Unit to a standard 70 MHz IF. A standard message FM demodulator can then be used to derive the original FDM baseband signal. Following de-emphasis (if required) and amplitude equalization/amplification, an FDM program channel demultiplexer will be required to recover the original program audio(s) which may either be input directly to the user's stereo/amplifier system or be remodulated into the FM broadcast band. From an implementation standpoint, the only advantage of FDM/FM compared to SCPC is that it imposes no increase in TVRO earth station frequency stability requirements, and RF tunability will not be necessary if all channels are multiplexed on one fixed frequency carrier.

In view of the amount and complexity of the equipment required for the radio program receiver under this scenario, FDM/FM might more appropriately be received instead by a community receiver. In this case, remodulation for monophonic or stereophonic FM transmission via low power transmitters would appear to be the most cost-effective means for delivering radio programming to the end users.

One approach to reducing the incremental cost of the FDM/FM radio program receiver for home reception is to use a single wide band FM demodulator for alternate TV or radio program reception, as illustrated in Figure 3.6. Separate second stage downconversion and IF and de-emphasis filtering (unless carrier band-widths are identical) would still be required on a switch selectable basis. This technique has the disadvantage of not permitting simultaneous TV and radio program reception (in particular TV sound channel could not be included with radio programs).

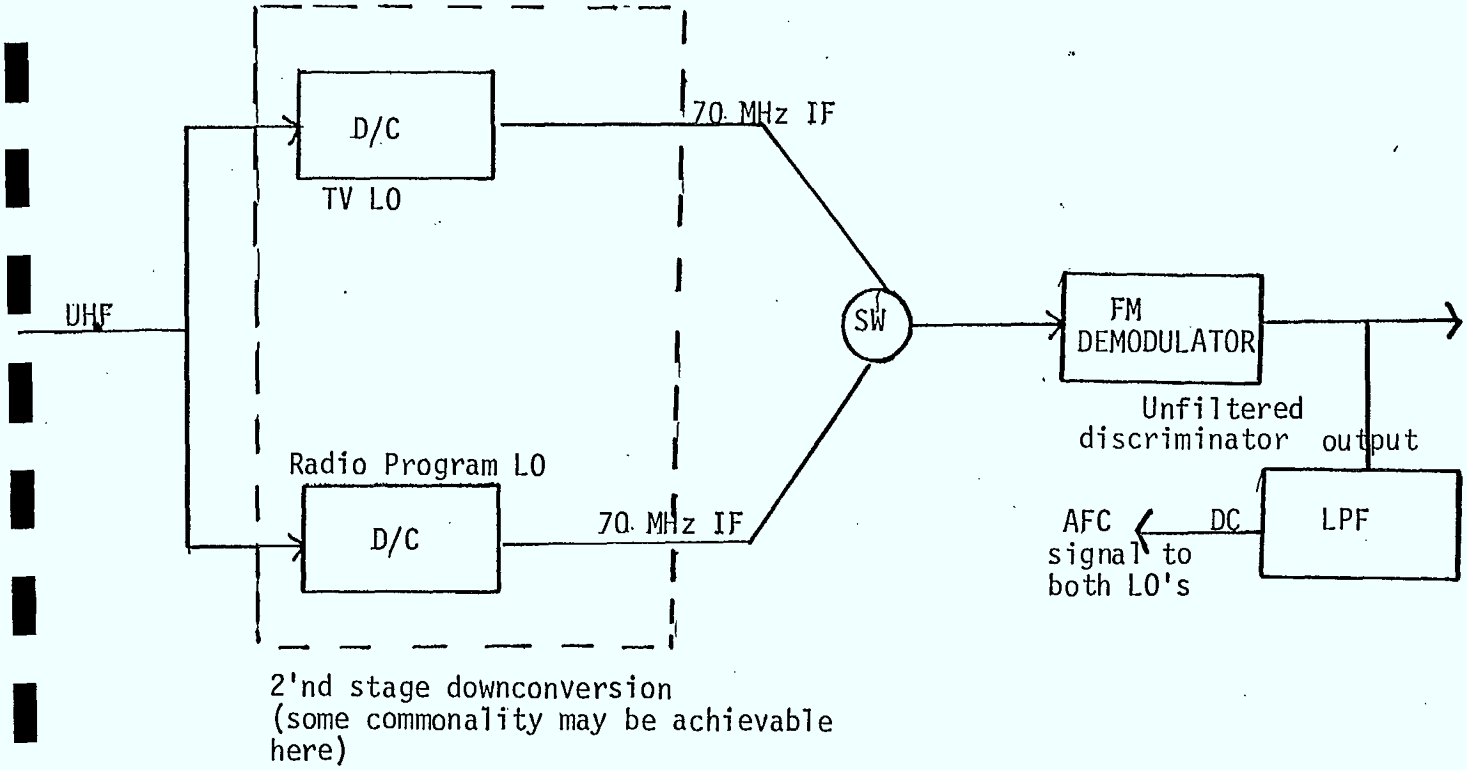


FIGURE 3.6 SINGLE DEMODULATOR ARRANGEMENT FOR ALTERNATE TV - FDM/FM RADIO PROGRAM RECEPTION

3.4.5 Flexibility and Growth Potential

An FDM/FM approach is inflexible in that it requires that all program channels for broadcast be back hauled to a single transmitter location. Unlike SCPC, growth in the number of FDM channels may require modification of the receiver IF bandwidth, de-emphasis network and SSB tuning range. Frequency planning constraints may be more (contiguous bandwidth is required for FDM carrier) or less (SCPC system is more sensitive to intermodulation and adjacent satellite interference) severe than with SCPC.

3.5 FM/FDM/FM

A scheme which combines the advantages of FM/SCPC and SSB/FDM/FM for monophonic sound reception at the expense of satellite power/bandwidth efficiency (see 5.1) is to directly modulate translated (starting at several hundred kHz) monophonic FM sound channels onto an FM carrier. This would:

(i) impose no change in required local oscillator stability or pose a difficult AFC problem (see 3.3.5)

(ii) potentially allow the TV demodulator to alternatively demodulate the FDM/FM sound channel carrier, removing need for "outer" demodulator

(iii) allow block translation (or external progam selection) without demodulation/remodulation (see 3.3.5)

Conventional FDM/FM pre-emphasis would be applied to ensure equalization of noise performance among the sub-carriers.

With respect to interference flexibility and growth potential the FM/FDM/FM system has the same characteristics as the SSB/FDM/FM system.

3.6 TDM/PSK

3.6.1 Power/Bandwidth Considerations

In the TDM/PSK/FDMA approach to radio program broadcasting, several program channels in digital format (PCM or DM) are time division multiplexed into a single, higher speed bit stream which then phase shift keys an IF carrier. Depending on the number of program channels, the TDM/PSK carrier may or may not share the transponder with other FDMA traffic. PSK/SCPC is thus a special case of TDM/PSK/FDMA in which only a single program channel is involved.

For a maximum of 20 monophonic program channels, the TDM bit rate will be approximately 8 Mbps (assuming 400 kbps for a high quality PCM or DM program channel, plus overhead framing bits). For 20 stereophonic program channels, the TDM bit rate would be doubled to 16 Mbps. Assuming DPSK modulation and a BT = 1.5, the transmission bandwidth required will either be 12 MHz (mono channels) or 24 MHz (stereo channels). Allowing for guardbands, the allocated RF bandwidth required would be about 14 MHz and 28 MHz respectively. For a mixture of twenty mono and stereo program channels, the bandwidth requirement will lie between these two extremes.

The TDM bit rate which can be supported by the satellite link for a desired probability of bit error varies directly with the available EIRP from the satellite and the DBS earth station G/T. Since the latter will be determined by the television transmission requirements, the saturated EIRP of the DBS satellite and output backoff (for FDMA operation only) to minimize IM interference will be key factors in determining the maximum allowable capacity of the TDM/PSK carrier. Coding could, of course, alleviate this situation somewhat by trading bandwidth for power but would further complicate the radio program receiver.

3.6.2 Interference Considerations

Since the effect of any interference into the TDM/PSK carrier will be to degrade the BER performance of the received traffic, this degradation can be mitigated entirely by increasing the available C/N_o (i.e., by allowing sufficient power margin) and a digital approach is hence a much more rugged system than FDM/FM/FDMA.

3.6.3 Incremental DBS Equipment Requirements

For TDM/PSK, the form of the radio program receiver will normally consist of a single stage of fixed downconversion from UHF to a 70 MHz IF (typically) followed by a PSK demodulator to recover the original TDM bit stream, a time division demultiplexer to separate out the various program channels and digital-to-analog conversion to obtain the original program channel audio. The audio signal(s) may either be input directly to a stereo/amplifier system (in the case of direct-to-home service) or be remodulated into the FM broadcast band (as in the case of a community DBS receiver).

Due to the higher bit rate (i.e. larger receive bandwidth and tolerable carrier recovery loop bandwidth) TDM/QPSK is not as sensitive as SCPC/QPSK to frequency uncertainty and phase noise. Nevertheless, depending on the number of sound program channels carried, some improvement in TVRO local oscillator stability might be required to support coherent QPSK operation. As in 3.3.3, we might therefore again contemplate differential demodulation techniques (DPSK or DMSK) which would not necessitate any improvement in down converter performance.

In view of the relative complexity and cost involved in providing a fairly sophisticated high speed digital demodulator and demultiplexer using presently available digital radio technology, a TDM/PSK approach to radio program distribution is probably more appropriate for community rather than individual reception.

3.6.4 Flexibility and Growth Potential

As in the case of FDM/FM, TDM/PSK lacks the uplink access flexibility of SCPC but, on the other hand, it makes more efficient use of bandwidth and is not as prone to IM and adjacent satellite interference. This implies more efficient use of satellite power and allows use of a smaller receive antenna.

The extent to which the number of program channels can be increased will again be determined by the transmission bit rate which can be supported by the satellite link. However, any change in the transmission rate will require significant modification to all DBS receivers, which effectively limits this option.

3.7 TDMA

TDMA provides the multiple access capability that TDM/PSK inherently lacks but at the cost of:

1. Increased overhead in a TDMA frame to accommodate guard times and preambles required for multiple accesses. Thus, for the same information throughput, TDMA will require a higher transmit bit

rate and hence a wider RF bandwidth in which to transmit.

2. A higher C/N_o requirement, as a result of the higher transmit bit rate and and E_b/N_o penalty imposed by the need to serially demodulate independent bursts, in order to achieve the same BER performance as TDM/PSK.

3. Increased equipment complexity at both the transmitter and the receiver due to the burst mode of operation (e.g., frame and burst synchronization circuitry, compression/expansion buffers and read/write control circuitry, as well as a more sophisticated demodulator). Since TDMA is being considered here within the context of radio program broadcasting, i.e., uni-directional information flow, the added terminal complexity engendered by its use in order to utilize only its multiple access feature may well require a great deal of justification.

TDMA should only be contemplated as a flexible means of centralizing program material required for direct-broadcast by non-SCPC means, and possibly for direct reception at the community level.

3.8 SSMA

Under certain conditions, a spread spectrum format can alleviate intra-and inter-satellite interference problems without necessarily penalizing terminal costs. The resulting advantages include:

i) SSMA permits narrowband traffic to be added to a transponder in which interference (intra-satellite, inter-satellite or terrestrial) free bands are not available.

ii) SSMA interference (both direct and from resulting IM products) into co-channel carriers simply adds on a power basis to their downlink thermal noise.

iii) SSMA ensures the downlink flux density/4 kHz limit is satisfied when broadcasting to very small aperture receive terminals.

iv) SSMA provides a multiple access capability (although not in a bandwidth efficient manner) without need for frequency agility (i.e., synthesizer).

v) Some increase in security is achievable through code selection.

Whenever excess power exists, SSMA derives its greatest advantage in being able to utilize an otherwise congested spectrum that would preclude access by any other technique in order to provide a limited amount of additional capacity. One important example in which SSMA could prove useful is the addition of limited capacity (e.g., 1-4 monophonic radio program channels) to a saturated FM/TV carrier in a transponder [39].

As a straightforward multiple access technique, however, direct sequence SSMA is highly bandwidth inefficient and the low-cost receiver necessary for DBS applications represents significant and high-risk (from an economic viability standpoint) new development.

4.0 SUMMARY OF PRELIMINARY COMPARISON

In the preceding sections, a number of candidate baseband multiplexing and RF transmission techniques, in appropriate pairwise combinations, have been qualitatively reviewed for the purposes of determining each pairing's relative merits and demerits for the distribution of radio programming within the context of a direct broadcasting satellite (DBS) scenario. Both digital and analog techniques have been considered in these determinations.

Since the provision of up to 20 high-quality (15 kHz) monophonic and stereophonic radio program channels is approached from the viewpoint of augmentation of service to an existing direct-to-home DBS TV infrastructure, a key consideration has been to determine, in a qualitative sense, the cost impact which various multiplexing/transponder access combinations might have on the DBS TVRO terminal, based on the perceived complexity of the radio program receiver that will be required under each distribution scenario.

To assist in summarizing these deliberations, Table 4.1 has been prepared. It attributes to each modulation/access combination a subjective ranking for each of six parameters which are perceived as being important in evaluating the feasibility of augmenting radio programming to DBS TV, viz:

(a) Uplink flexibility

(b) Growth flexibility

(c) Incremental TVRO costs

(d) Satellite efficiency

(e) Ease of obtaining high-quality audio

(f) Sensitivity to adjacent satellite interference.

It is apparent from a review of Table 4.1 that the only modulation/access techniques which can readily be rejected are those associated with spread spectrum and TDMA. Further in-depth evaluation of the remaining modulation/access techniques applied to specific DBS scenarios is required to establish which options are most economic under which circumstances.

<table>
<tr><th colspan="2">Access
Modulation</th><th>SCPC**</th><th>TV
Sub-Carrier</th><th colspan="2">Single Carrier**</th></tr>
<tr><td></td><td></td><td></td><td></td><td>SSB/FDM</td><td>FM/FDM</td></tr>
<tr><td>FM</td><td>A</td><td>Good</td><td>Bad</td><td colspan="2">Moderate-to-Bad</td></tr>
<tr><td></td><td>B</td><td>Good</td><td>Bad</td><td colspan="2">Moderate-to-Bad</td></tr>
<tr><td></td><td>C</td><td>Moderate</td><td>Good</td><td>Mod.-to-Bad</td><td>Good</td></tr>
<tr><td></td><td>D</td><td>Moderate</td><td>Good</td><td>Mod.-to-Bad</td><td>Bad</td></tr>
<tr><td></td><td>E</td><td>Moderate</td><td>Moderate</td><td colspan="2">Moderate</td></tr>
<tr><td></td><td>F</td><td>Bad</td><td>Moderate</td><td colspan="2">Moderate</td></tr>
<tr><td></td><td></td><td></td><td></td><td>TDM</td><td>TDMA</td></tr>
<tr><td>Digital</td><td>A</td><td>Good</td><td>Bad</td><td>Moderate</td><td>Good</td></tr>
<tr><td></td><td>B</td><td>Good</td><td>Bad</td><td colspan="2">Moderate</td></tr>
<tr><td></td><td>C</td><td>Moderate-to-Bad</td><td>Moderate</td><td>Bad</td><td>Very Bad</td></tr>
<tr><td></td><td>D</td><td>Moderate</td><td>Good‡</td><td colspan="2">Moderate-to-Good</td></tr>
<tr><td></td><td>E</td><td>Good</td><td>Good</td><td colspan="2">Good</td></tr>
<tr><td></td><td>F</td><td>Moderate-to-Bad</td><td>Moderate-to-Good</td><td colspan="2">Good</td></tr>
<tr><td>Spread Spectrum</td><td>A</td><td>Good</td><td>Bad</td><td colspan="2">N/A</td></tr>
<tr><td></td><td>B</td><td>Moderate-to-Bad</td><td>Bad</td><td colspan="2"></td></tr>
<tr><td></td><td>C</td><td>Bad</td><td>Moderate-to-Bad</td><td colspan="2"></td></tr>
<tr><td></td><td>D</td><td>Bad*</td><td>Moderate</td><td colspan="2"></td></tr>
<tr><td></td><td>E</td><td>Good</td><td>Good</td><td colspan="2"></td></tr>
<tr><td></td><td>F</td><td>Good</td><td>Good</td><td colspan="2"></td></tr>
</table>

*May avoid need for second transponder to support a small number of SCPC carriers

**Dedicated versus shared (with TV) transponder use may influence B & D

‡Video performance sensitive to presence of multiple subcarriers

A: Uplink Flexibility
B: Growth Flexibility
C: Incremental TVRO Costs
D: Satellite Efficiency
E: Ease of Obtaining High-Quality Audio
F: Sensitivity to Adjacent Satellite Interference

TABLE 4.1: COMPARISON OF MODULATION/ACCESS TECHNIQUES FOR DBS RADIO PROGRAMMING DISTRIBUTION

5.0 SATELLITE POWER AND BANDWIDTH REQUIREMENTS

5.1 Introduction

A quantitative comparison of satellite utilization efficiencies for the viable candidates in 4.0 was undertaken and results presented in Figures 5.1 - 5.3. In these graphs transponder power and bandwidth relative to that required for a single DBS video carrier with associated audio, viz*

C/N = 14.0 dB clear weather with an 18 MHz noise bandwidth,

are plotted versus number of 15 kHz monophonic sound channels. The cases considered with assumptions made are listed below.

(a) Dedicated Radio Program Transponder

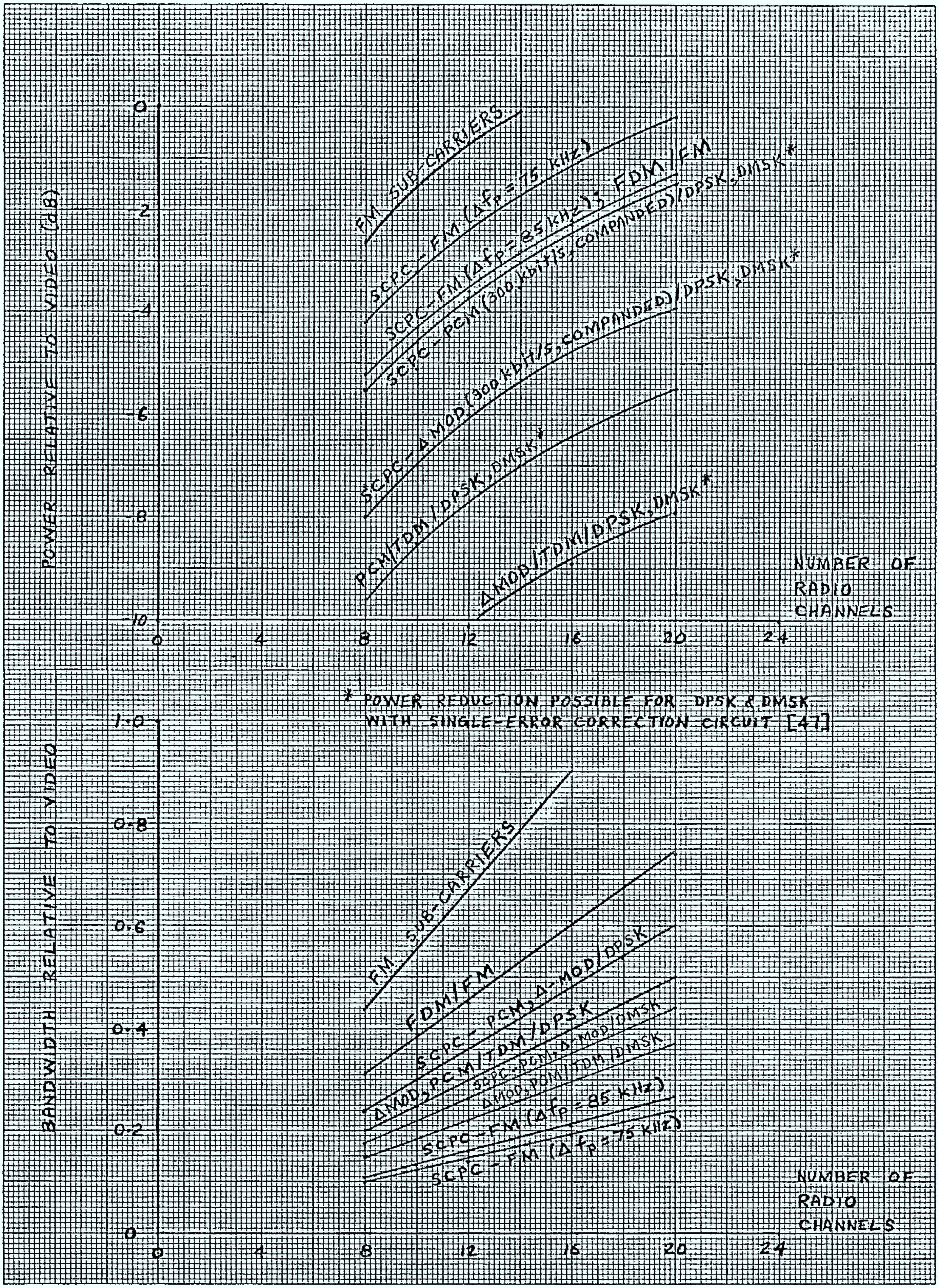
1. SCPC-FM, peak deviation = 75 kHz, carrier separation = 10 kHz (i.e. compatible with monophonic reception in home FM receiver), weighted S/N = 52 dB non-companded, (companding would not be applied for demodulation by home FM receiver).

2. SCPC-FM, peak deviation = 85 kHz (CTS value), carrier separation = 240 kHz weighted S/N = 52 dB non-companded, 60 dB subjective equivalent companded.

3. Companded 2 phase DPSK 300 kbps SCPC-PCM, carrier separation = 540 kHz subjective equivalent weighted S/N = 60 dB.

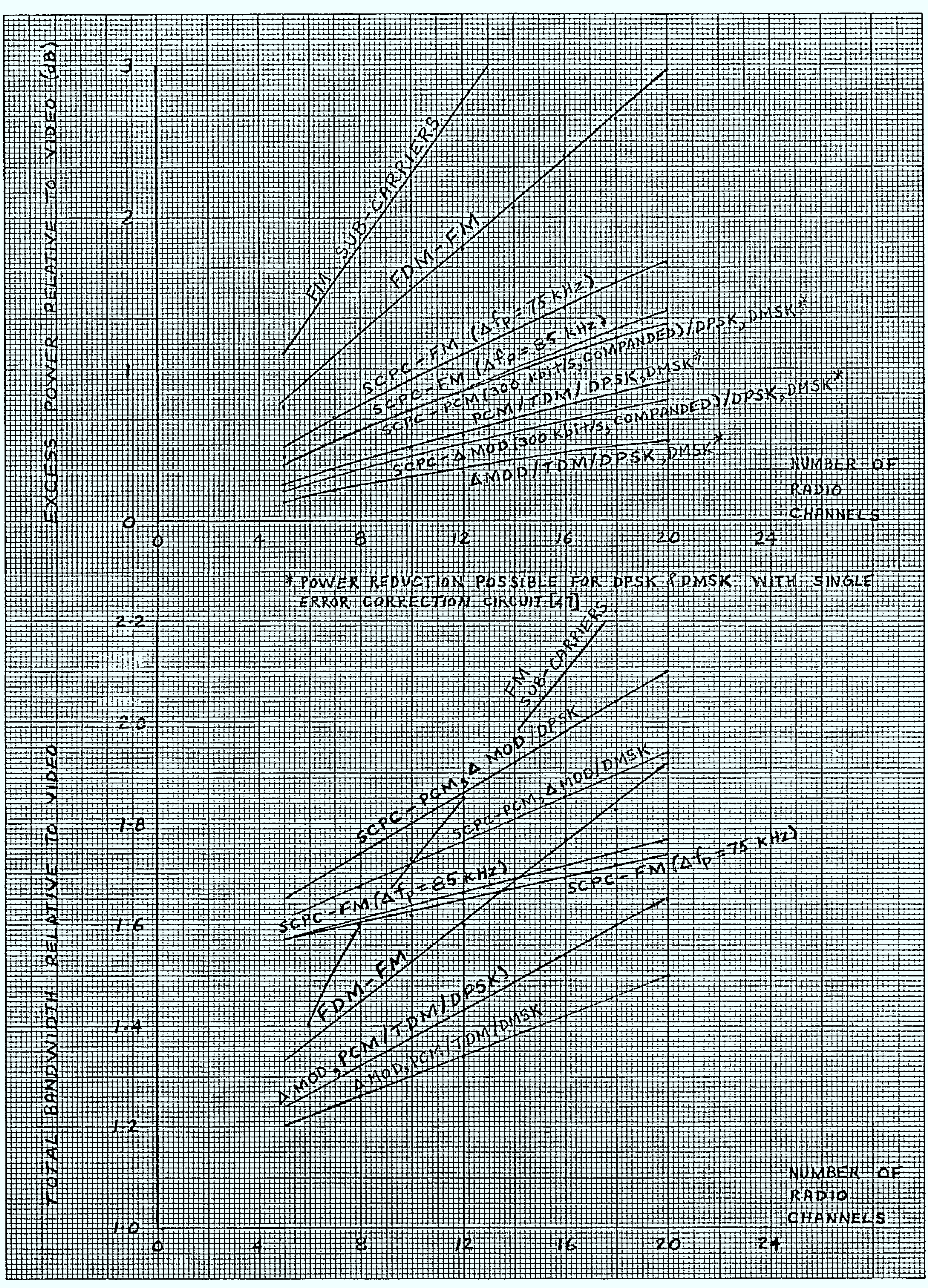
---

*As defined in CRC memo 7512-1 R. Douville to file dated 21 April 1981.



* POWER REDUCTION POSSIBLE FOR DPSK & DMSK WITH SINGLE-ERROR CORRECTION CIRCUIT [47]

FIGURE 5.1 DEDICATED RADIO PROGRAM TRANSPONDER



* POWER REDUCTION POSSIBLE FOR DPSK & DMSK WITH SINGLE ERROR CORRECTION CIRCUIT [47].

FIGURE 5.2 SHARED VIDEO/RADIO PROGRAM TRANSPONDER

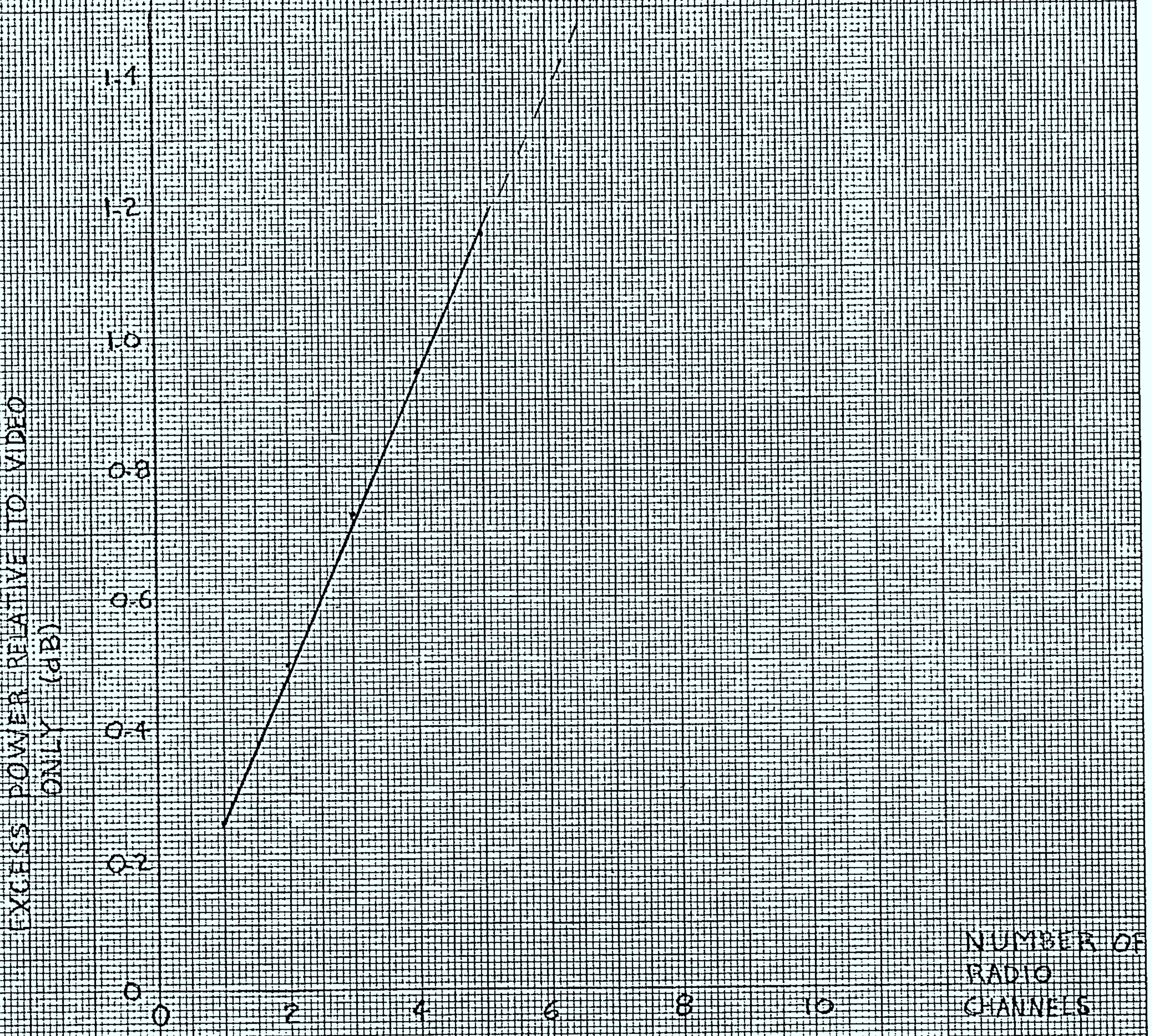


FIGURE 5.3 RADIO PROGRAMS ADDED ABOVE VIDEO BASEBAND

4. Companded 2 phase DPSK 300 kbps SCPC-Δ, carrier separation = 540 kHz subjective equivalent weighted S/N = 60 dB.

5. SSB/FDM/FM, FDM channel spacing = 18 kHz, weighted S/N = 52 dB non-companded, 60 dB subjective equivalent companded.

6. FM/FDM/FM, same parameters as in 2.

7. Companded 2 phase DPSK 300 kbps per channel TDM-PCM, subjective equivalent weighted S/N=60 dB.

8. Companded 2 phase DPSK 300 kbps per channel TDM-Δ, subjective equivalent weighted S/N=60 dB.

9. In all above DPSK cases, DMSK is also considered.

Assumptions:

1. Number of radio program channels ≥8 (validates assumption 2 below)

2. 4.5 dB output backoff plus 0.5 dB degradation due to IM and contiguous occupancy assignments for SCPC (as discussed in 3.3.3, this is least efficient use of power, most efficient use of bandwidth case).

3. 20% guard bands for SCPC, except for FM stereo compatible system (large guard band eases earth station filtering requirements).

4. SSB/FDM/FM loading factor per channel = 0 dB (i.e. no. multi-channel loading advantage as in telephony) and peak factor = 17.24 - 3 log (# channels) (same as telephony)*.

---

*For companded channels this peak factor could probably be reduced resulting in a lower C/N_o requirement than that shown in Figures 5.1 and 5.2.

5. FM/FDM/FM peak-to-rms factor = 10log(N) dB for ≤ 10 channels, 10+5log(N-10)dB for $10 \leq N \leq 20$ channels.

6. FDM/FM C/N in Carson's Rule bandwidth fixed at 14 dB (i.e. power limited operation with 4 dB threshold margin).

7. Threshold BER for 300 kbps PCM sound channel = 10^{-5}.

8. Threshold BER for 300 kbps Δ sound channel=10^{-3}.

9. DPSK carrier bandwidth = 1.5 x data rate (i.e. 50% rolloff).

10. DMSK carrier bandwidth = 1.1 x data rate

11. 1 dB output backoff plus nonlinear TWT distortion loss for TDM/PSK carrier.

(b) Shared Video/Radio Program Transponder

Previous cases repeated

Assumptions:

1. Number of radio program channels ≥ 5 (ensures no subjective effect of coherent IM products - see last two paragraphs of 3.3.1.2 - validating assumption 3 below).

2. 9 MHz guard band between video and SCPC carriers (see Figure 3.3) to minimize IM to SCPC carriers.

3. 2 dB excess transponder power in video plus SCPC cases for output back off plus IM degradation losses.

4. Guard band between video and FDM or TDM radio program carrier = 1.8 MHz + 10% radio program carrier bandwidth (large guard band eliminates 2A-B IM product interference and eases station filtering requirements).

5. The two carrier output backoff loss versus carrier power ratio of Figure 5.4 is applied.

6. Degradation due to IM interference from <u>adjacent</u> DBS transponder(s) not considered (This can be controlled by appropriate combination of inter-transponder guard band and TWT output multiplex filter, although it still might be significant for saturated 2 carrier operation of the transponder).

(c) Video Sub-Carriers

1. FM SCPC sub-carriers, peak deviation = 75 kHz, compatible with tuning and demodulation by home stereo receiver, weighted S/N = 52 dB.

Assumptions:

1. Carson's Rule Bandwidth held fixed (18 MHz), implying video deviation reduced to accomodate sub-carriers, C/N_o increased to maintain constant video SNR.

2. In Carson's Rule equation, top baseband frequency fixed at 4.2 MHz and video and sub-carrier deviations added on a root sum square basis.

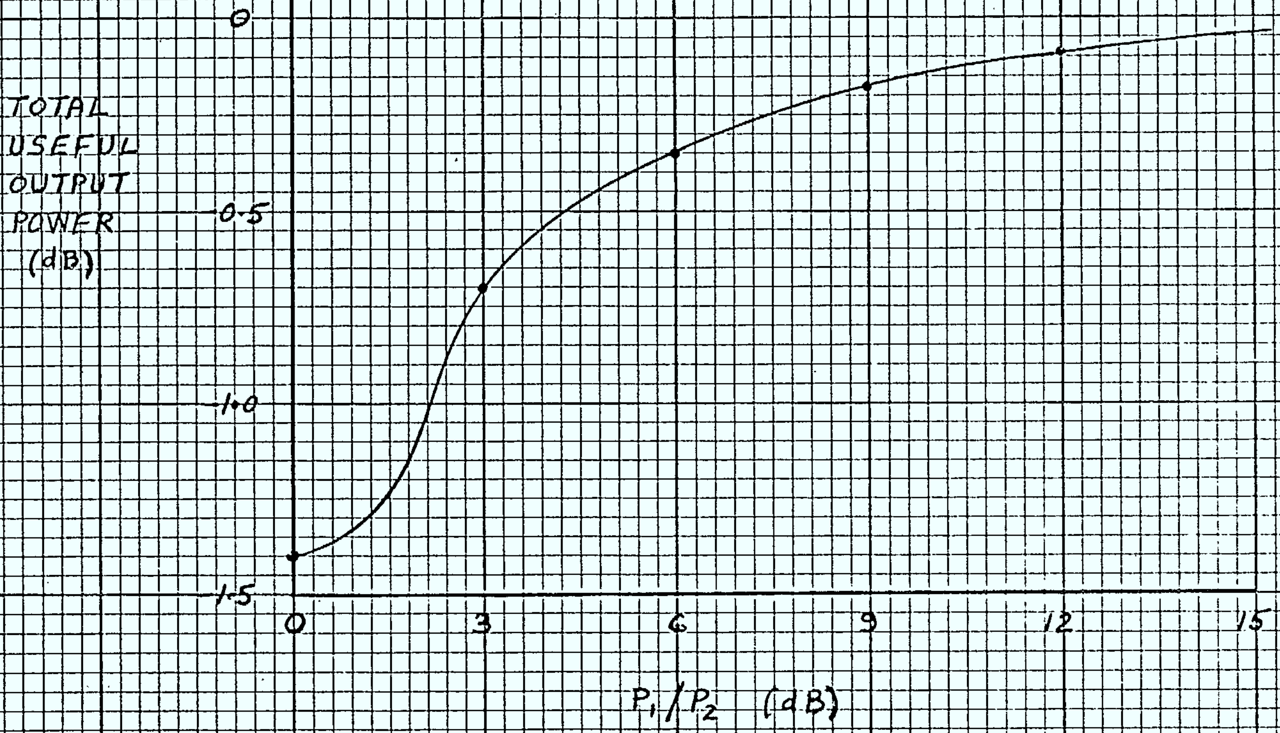


FIGURE 5.4 TWO CARRIER OUTPUT POWER LOSS

3. A nominal subcarrier frequency of 6.8 MHz is used to establish required subcarrier deviation on TV carrier. (Because the demodulated noise spectral density increases as the square of the baseband frequency, deviation is a function of subcarrier frequency. Assuming subcarriers are added in increasing order of frequency, Figure 5.3 should therefore be slightly concave up to account for an increasing deviation with number of channels.)

4. The above assumptions are applicable only for a small (<5 typically) number of sound channels. Problems of crosstalk among the sub-carriers and interference into the video could result in a further bandwidth and power penalty not predicted by this analysis.

The equations required to perform C/N_o and bandwidth calculations for each of the above cases are presented in the Appendix.

5.2 Interpretation of Results

An examination of the results depicted in Figures 5.1 - 5.3 yields the following observations:

1. Digital SCPC is more power efficient and less bandwidth efficient than FM SCPC. (The power efficiency of FM SCPC can be made to approach that of the digital system through the use of syllabic companders). Also, transmission of a stereo program requires only one digital SCPC link (i.e. one receive channel unit) compared to two for efficient FM SCPC transmission.

2. For dedicated transponder operation digital multiplexing saves 4-5 dB of satellite power over SCPC operation. With a shared transponder the power saving is only about 1 dB, but there is also a bandwidth saving of about 9 MHz. Also there is no possibility of subjective degradation of the video due to coherent IM products as discussed in 3.3.1.2.

3. As expected, addition of TV associated subcarriers makes the most efficient use of satellite bandwidth and power, under the assumption of a constant composite rms deviation. Note that only the extreme case of excess power (no excess bandwidth required) has been considered here.

4. SSB/FDM/FM compares less favourably for sound program transmission than it would for telephony, due to higher activity (loading factor) and dynamic range requirements per channel. Individual channel companding will not only increase SNR as indicated in 5.1a(5), by reducing intelligible crosstalk into idle channels, it will allow significant reduction (for small number of channels) in the composite peak factor and hence carrier power and bandwidth in Figures 5.1 and 5.2.

5. As expected the FM/FDM/FM (or FM sub-carriers only) approach is least efficient in terms of satellite power and bandwidth required assuming conventional Carson's Rule analysis. Since the FM sub-carriers are more tolerant than FDM channels to intermodulation distortion, improvement in the plotted power/bandwidth efficiency may be possible.

6. The power saving advantages of digital multiplexing (see 2 above) probably do not overcome the implementation disadvantages discussed in 3.6. Unless adjacent satellite interference is expected to be a problem, this technique can be eliminated from consideration for implementation in the near term (i.e. using present day technology) for economic reasons.

7. The power/bandwidth penalty in using home receiver compatible FM SCPC transmission parameters for <u>monophonic broadcasting</u> is not significant, let alone prohibitive.

6.0 CONCLUSIONS

1. The following options were given preliminary evaluation in terms of flexibility, incremental earth station cost, satellite utilization efficiency, audio channel quality and susceptibility to interference:

   Transponder Utilization
   - dedicated transponder for radio program
   - transponder shared with TV DBS-separate radio program RF carrier(s)
     - -TV sub-carrier(s)

   Radio Program Multiple Access
   - single uplink - CW carrier
     - - TV sub-carrier(s)
   - multiple uplinks - single channel per carrier FDMA
     - - TDMA
     - - SSMA

   Encoding/Multiplexing
   - VF and companded VF (for FM SCPC only)
   - SSB/FDM and companded SSB/FDM (for FM modulation only)
   - FM/FDM (for FM modulation only)
   - companded PCM (for digital modulation only)
   - companded Δ-mod (for digital modulation only)
   - TDM (for digital modulation only)
   - direct sequence spreading (for digitally modulated TV sub-carrier only)

   Modulation
   - pre-emphasized FM
   - binary DPSK
   - coherent QPSK
   - MSK (or FFSK)

2. For a small number (<3) of sound channels per video channel, the FM sub-carriers technique is most promising. The only addition to the TVRO earth station required for alternate TV or single radio program direct to user reception is a tuning stage prior to the sub-carrier receiver already existing in the TVRO. Multiple inexpensive sub-carrier receivers in a community TVRO would allow all channels to be simultaneously accessed.

3. For a larger number of sound channels, SCPC is most promising [uncompanded FM with external tuning only for moderate quality monophonic channels, binary DPSK or DMSK probably with Δ encoding for high quality stereo sound channels], providing a low cost AFC technique can be implemented and adjacent satellite interference problems can be avoided.

4. If AFC or adjacent satellite interference problems with SCPC prove difficult to overcome economically, SSB/FDM/FM with individual channel companding or FM/FDM/FM should be considered. The latter offers the possibility of external tuning only for monophonic sound channels at the expense of satellite power/bandwidth utilization. In either case, the TV FM demodulator should be designed to permit alternate radio program carrier demodulation.

5. With either SCPC or FDM/FM, a greater adjacent satellite interference protection ratio is needed. This introduces potential co-ordination problems which could limit or preclude the use of SCPC with unmodified TVRO antennas. In the FDM/FM case, the problem is less severe and becomes one of allocation in an overall noise budget.

6. Combining sound channels on a high speed TDM carrier is presently not economically attractive. Developments in digital radio technology and the introduction of digital stereo home receivers could make this option attractive especially for high quality stereo distribution.

7. For an SCPC system use of a separate transponder saves about 2 dB in satellite power and up to 5 MHz (9 MHz minus inter-transponder guard band) in bandwidth. For an FDM/FM system there is only about a 1 dB power saving and no bandwidth advantage. However, problems associated with the generation of large 2A-B IM products, which will likely further penalize the power and bandwidth efficiency of the single transponder system, are avoided. Assuming the planned EIRP and bandwidth of the DBS transponder can be increased to accomodate the addition of radio program traffic, it is not obvious that separate transponder(s) are justified.

7.0 PROPOSED FURTHER STUDY

Further study is clearly required before reasonable tentative specifications and cost estimates for an incremental radio program satellite direct broadcast distribution system can be developed. The direction of such study will to a large extent depend on more definitive input on:

- maximum number of radio program channels the system must support
- number of video channels to be broadcast
- demand for stereo versus monophonic channels
- need for simultaneous TV and radio program reception in a home

(The above are largely dependent on the user's willingness to pay for enhanced service)

- characteristics of DBS compatible TVRO earth station (technical specifications and cost)
- constraints on adjacent satellite interference
- constraints (if any) on DBS satellite transponder configuration and frequency plan
- projected number of DBS TVRO earth stations
- projected distribution and number of program origination points (are separate uplinks required?)

- industrial benefit objectives (see 1.2)

It is believed that this report has identified all the factors which should be taken into account in selecting the most promising approach to direct broadcast radio program distribution. Further systems engineering is required, particularly to establish:

- number of sound channels which can effectively (i.e. without reduction in composite FM deviation) be carried by SCPC or a multiplexed video sub-carrier(s),
- whether TVRO antenna gain specification must be modified to ensure adequate adjacent satellite interference protection of SCPC radio program signal(s),
- extent to which TVRO local oscillator stability and existing AFC subsystems must be improved to ensure adequate SCPC radio program demodulator performance,
- whether high speed digital transmission techniques will be economically viable for direct broadcasting applications in the medium to long term,

is required, as well as quantification of costs for comparison purposes, will be necessary to rationalize this selection (Note that a radio program system candidate must bear the incremental cost of any TVRO earth station subsystem upgrade it necessitates). While the evaluation could be performed for each candidate on a parametric basis, it would be more usefully directed towards a particular perceived service scenario, i.e. the data requested on the previous page should be made available prior to further analysis.

Once the specific approach for the defined service scenario is identified, further systems engineeering (including detailed tradeoff analysis such as PCM versus delta encoding for digital SCPC) is required to derive tentative performance and design specifications for the transmitter, DBS satellite transponder and receiver. (Emphasis will be placed on the receiver as the most important determinant of economic viability if the assumed number of such receivers is sufficiently large). Since the outcome of this study is uncertain, a second review of options could follow.

Once reasonable specifications for the system have been derived, a more rigorous economic model aimed at determining absolute cost rather than identifying the lowest cost option should be applied. This will take realistic account of non-recurring and recurring cost elements, world market size, capital and operating cost components, and the impact of technological development in the time frame for deployment.

Regulatory and co-ordination questions should also be given technical and "political" assessment, either prior to or following the assessment of economic viability.

REFERENCES

[1] "A Study of the Radio Distribution Systems of the CBC Northern Service", Prepared by Miller Communications Systems Ltd. for the CBC Northern Service, August 1979.

[2] R. R. Bowen et al, "The Development of a Canadian Broadcasting Satellite System at 12 GHz", ICC, Seattle, WA., June 1980, pp. 51.3.2 - 51.3.5.

[3] C. A. Billowes et al, "Low-Power Direct Broadcasting Satellite Trials in Canada", International Broadcasting Conf., London, England, September 1980.

[4] J. W. B. Day et al, "The Applications of Lower Power Satellites for Direct Television Broadcasting", XXXth Congress of the International Aeronautical Federation, Munich, F.R.G., September 17-22, 1979, pp. 1417 - 1431.

[5] J. G. Chambers, "An Evolutionary Approach to the Introduction of Direct Broadcasting Satellite Service",

[6] W. Zatychec, "Anik C Space Segment for Telesat Canada", AIAA 8th Communications Satellite Systems Conf., Orlando, Florida, April 20 - 24, pp. 32 - 40.

[7] "A Study of the Cost/Performance Tradeoffs for Regional Television Distribution via Satellite", Prepared by Miller Communications Systems for the DOC, March 1976.

[8] "Performance Specifications for TV-Associated Sound Program Transmission Using the FM-Subcarrier Technique", INTELSAT Document BG-35-78E, December 1978.

[9] CCITT Orange Book Rec. J.21 Geneva 1976.

[10] CMTT Report 293-1 1966, "Audio frequency parameters for stereophonic reproduction of sound".

[11] J. W. Johnson, "Program audio terminology", Coastcom Ltd, October 1975.

[12] R. Evans Wetmore, "DATE: A digital audio system for television", SMPTE, October 1975.

[13] C. R. Caine et al, "NICAM-3 A companded PCM system for the transmission of high quality sound-programmes", IBC 1980.

[14] Conversation with B. Bryden, CRC, Ottawa.

[15] Conversation with D. Wohlberg. SED, Saskatoon.

[16] W. R. Daumer and J. R. Cavanaugh, "A Subjective Comparison of Selected Digital Codecs For Speech", Bell System Technical Journal, November 1978.

[17] "Principles of Communication Systems", Taub and Schilling, McGraw-Hill, 1971.

[18] R. Placek and H. Wegener, "Audio-Plexing: a Method to Expand Satellite Capacity", Satellite Communications, February 1980.

[19] S. Dinsel, "Stereophonic Sound And Two Languages in TV, the Double-Sound Carrier Method", IBC 1980.

[20] CCIR DOC 9/113 "Transmission of Sound And Vision Signals by TDM or FDM", May 1976.

[21] J. S. Butterworth, "The Use of Audio Subcarriers For the CTS TV Relay Experiment", CRC Technical memorandum SS 13/73, April 1973.

[22] Conversation with R. Huck, CRC, Ottawa.

[23] Y. Numaguchi, "Present Status of Multi-Channel Sound Television Broadcasting in Japan", IEEE Trans. Broad. vol BC-25 no. 4 December 1979.

[24] H. Nakajima, "An FM-FM Multiplex Sound System", Broadcaster, October 1980.

[25] CCIR Doc 10 - 11S/7 "Modulation Systems For the Sound Signals Accompanying Television Pictures in Satellite Broadcasting".

[26] N. H. C. Gilchrist, "Satellite Broadcasting; the Feasibility of Adding a PSK Subcarrier Sound Signal to an FM Television Signal", BBC Research Dept Report RD 1976/8.

[27] D. C. Coll and N. Zervos, "The Use of Spread Spectrum Modulation for the Co-channel Transmission of Data and Television", NTC 1979.

[28] Weinhouse, N. P. "Impact of Video Transmission Requirements on Satellite Systems", NTC, New Orleans, December 1975.

[29] Aasterud, J. P., "A Review of TV Performance Calculations for Satellite Links", (reference unknown).

[30] R. K. Kwan, "Television and Radio Program Distribution in Canada", European Broadcasting Conference, 1975.

[31] W. F. Callanan, et al, "Multiple Carrier Transmissions in Satellite Transponder", NTC, Houston, Texas, November 1980, pp. 30.4.1 - 30.4.8.

[32] W. L. Hetrich, "An Improved Multichannel Program Distribution System to Serve the Broadcaster", NTC, Washington, D.C., December 27 - 29, 1979, pp. 12.4.1 - 12.4.6.

[33] CCIR Document No. 10-11S/48-E.

[34] F. G. Stremler, "Introduction to Communication Systems", Addison-Wesley, January 1979, pp. 280-283.

[35] R. J. F. Fang, and W. A. Sandrin, "Carrier Frequency Assignment for Nonlinear Repeaters", Comsat Tech. Review, vol. 7, no. 1, Spring 1977, pp. 227 - 245.

[36] "Cost Effective Options for the Thin Route and TV Broadcasting Network of Northern Canada", Prepared by Miller Communications Systems Ltd. for the DOC, April 1976.

[37] J. W. Johnson, "Program Audio Frequency Division Multiplexing Techniques for Satellite Networks", Proc. of 1975 Midwest Symp. on Circuits and Systems, pp. 58 - 62.

[38] J. W. Whelan, "Analog-FM vs. Digital PSK Transmission", IEEE Trans. on Comms., Vol. COM-14, no. 3, June 1966, pp. 275 - 282.

[39] R. Lyons and K. Tiedemann, "A Low Cost Spread Spectrum Multiple Access Channel Unit for Low Capacity Satellite Links", URSI XX'th General Assembly, Washington DC, August 10 - 19, 1981.

[40] A. Bairi and J. Leonhard, "A Domestic Satellite Communications System for Algeria", 1975 ICC 1975, San Francisco, pp. 12 - 23.

[41] "Simulation and Analysis of Simultaneous Video and SCPC Operation in an RF Channel", study undertaken by Telesat Canada for Western Union Telegraph Co. (author: R.G. Lyons), September 1975.

[42] "A Feasibility Study of a 12/14 GHz SCPC Satellite Communications System to Meet Telephony Requirements in Rural Areas", Prepared by Miller Communications for the DOC, August 1978.

[43] R. G. Lyons, "A Stochastic Analysis of Signal Sharing in a Bandpass Nonlinearity", IEEE Trans. Communications, Vol. COM-22, no.11, November 1974, pp. 1778 - 1788 (see III, Example B).

[44] L. S. Golding, "Transponder Multipath Effects on Digital Satellite Communications", ICC-74, Minneapolis, June 17-19, pp. 364-1, -5.

[45] Presentation by Telesat Canada to CBC of results of investigation of feasibility of adding radio program carriers to existing CBC TV transponders, April 1979 (reference: Fred Smart).

[46] R. McClure, "Analysis of Intermodulation in an FDMA Satellite Communications System with a Bandwidth Constraint", ICC 70, pp. 8-29, -36.

[47] T. Masamura et al, "Differential Detection of MSK with Nonredundant Error Correction", IEEE Trans. Communictions, June 1979, pp. 912-918.

APPENDIX

FORMULAS USED TO CALCULATE SATELLITE POWER AND BANDWIDTH REQUIREMENTS FOR RADIO PROGRAM

A.0 Dedicated Radio Program Transponder

The power used relative to the power required by a single video signal is given by

$$r = \frac{\left(\frac{C}{N_o}\right)_{radio}}{\left(\frac{C}{N_o}\right)_{video}}$$

$\left(\frac{C}{N_o}\right)_{video}$ is given by

$$\left(\frac{C}{N_o}\right)_{video} = 14 + 10\log_{10}(18 \text{ MHz})$$

$$= 86.6 \text{ dB} - \text{Hz}$$

$$= 4.57 \times 10^8, \text{ absolute units}$$

The bandwidth used relative to that used by a video signal is given by

$$q = \frac{B_{radio}}{18 \text{ MHz}}$$

The following formulas are used for specific access modes.

A.1 SCPC-PCM/DPSK

$$\left(\frac{C}{N_o}\right)_{PCM} = \left(\frac{C}{N_o}\right)_{per\ access} + 10\log_{10}N_A + \text{loading degradation}$$

$$= 67.1 + 10\log_{10}N_A + 5,\ \text{dB} - \text{Hz}$$

$$= 72.1 + 10\log_{10}N_A,\quad \text{dB} - \text{Hz}$$

$$B_{per\ carrier} = 1.5\ R + 20\%\ \text{Guard Band}$$

$$= 540\ \text{kHz}$$

$$B_{PCM} = N_A \cdot B_{per\ carrier}$$

N_A = number of radio program channels

R = data rate per channel = 300 kbit/s

A.2 SCPC - ΔMOD/DPSK

$$\left(\frac{C}{N_o}\right)_{\Delta\ mod} = \left(\frac{C}{N_o}\right)_{per\ access} + 10\log_{10}N_A + \text{loading degradation}$$

$$= 64.7 + 10\log_{10}N_A + 5,\ \text{dB} - \text{Hz}$$

$$= 69.7 + 10\log_{10}N_A,\ \text{dB} - \text{Hz}$$

$$B_{per\ carrier} = 1.5R + 20\%\ \text{Guard Band}$$

$$= 540\ \text{kHz}$$

$$B_{\Delta\ mod} = N_A \cdot B_{per\ carrier}$$

A.3 SCPC-FM

$$\left(\frac{C}{N_o}\right)_{\text{per access}} = \left(\frac{S}{N}\right) + 10\log_{10}\left[\frac{2f_m^{\,3}}{3\Delta f_p^{\,2}}\right] - (P+W),\ \text{dB} - \text{Hz}$$

$$= 52-1.76+125.28 - 20\log_{10}\Delta f_p - 9.6$$

$$= 165.92 - 20\log_{10}\Delta f_p,\ \text{dB} - \text{Hz}$$

$$\left(\frac{C}{N_o}\right)_{\text{FM}} = \left(\frac{C}{N_o}\right)_{\text{per access}} + 10\log_{10}N_A + \text{nonlinearity degradation}$$

$$= 170.92 - 20\ \log_{10}\Delta f_p + 10\ \log_{10}N_A$$

$$B_{\text{per carrier}} = \text{Carson's Rule Bandwidth} + 20\%\ \text{Guard Band}$$

$$= 2(\Delta f_p + f_m) + 20\%\ \text{Guard Band}$$

$$= 2.4\ \Delta f_p + 36\ \text{kHz}$$

$$B_{\text{FM}} = N_A \cdot B_{\text{per carrier}}$$

A.4 PCM/TDM/DPSK

$$\left(\frac{C}{N_o}\right)_{\text{PCM/TDM}} = \left(\frac{C}{N_o}\right)_{\text{per channel}} + 10\log_{10}N_A + \text{nonlinearity degradation}$$

$$= 67.1 + 10\log_{10}N_A + 1,\ \text{dB} - \text{Hz}$$

$$= 68.1 + 10\log_{10}N_A,\ \text{dB} - \text{Hz}$$

$$B_{\text{PCM/TDM}} = N_A\ (1.5 \times R)$$

$$= N_A(450\ \text{kHz})$$

A.5 ΔMod/TDM/DPSK

$$\left(\frac{C}{N_o}\right)_{\Delta Mod/TDM} = \left(\frac{C}{N_o}\right)_{\text{per channel}} + 10\log_{10}N_A + \text{nonlinearity degradation}$$

$$= 64.7 + 10\log_{10}N_A + 1, \quad dB - Hz$$

$$= 65.7 + 10\log_{10}N_A, \quad dB - Hz$$

$$B_{\Delta Mod/TDM} = N_A\ (1.5 \times R)$$

$$= N_A (450\ kHz)$$

A.6 FDM/FM

The FM equation applicable to the radio program is

$$\left[\frac{S}{N}\right] = \left[\frac{C}{N_o}\right]_B \frac{3\ \overline{P}\ \overline{W}\ \Delta f_{tt}^2}{f_m^3 - (f_m - b)^3} \qquad (1)$$

where

$\left[\frac{S}{N}\right]$ = weighted test tone-to-noise ratio

= 52 dB

$\left[\frac{C}{N_o}\right]_B$ = $\frac{C}{N_o}$ in Carson's Rule bandwidth, B

b = single channel baseband bandwidth

= 15 kHz

f_m = maximum FDM bandwidth including allowance for multiplexing

= $N_A \cdot (18\ kHz)$

P = program weighting factor

$= 10\log_{10} \bar{P}$

= 6 dB (CCIR Recommendation 468-1)

W = pre-emphasis weighting factor

$= 10\log_{10} \bar{W}$

$$= \begin{cases} 3 \text{ dB}, & 2 \leq N_A \leq 6 \\ 4 \text{ dB}, & N_A \geq 6 \end{cases}$$

Δf_{tt} = test tone rms frequency deviation

$$= \frac{1}{\sqrt{2}} \Delta f_p$$

Δf_p = peak frequency deviation

$$\Delta f_{tt} = \frac{\Delta f_{rms}}{\ell}$$

ℓ = multi-channel loading factor

$L = 20\log_{10}(\ell)$

$\approx 10\log_{10} N_A$

$B = 2[g\Delta f_{rms} + f_m]$

$$= 2[g\ell\Delta f_{tt} + f_m] \qquad (2)$$

g = peak-to-rms voltage factor

$$G = 20\log_{10} g$$

$$= 17.24 - 3\log_{10} N_A, \quad N_A \leq 120$$

With C/N = 14 dB,

$$\left(\frac{C}{N_o}\right)_B = 14 + 10\log_{10} B,\ \text{dB - Hz} \qquad (3)$$

Substitute (2) into (3) and use the result in (1). Solving for Δf_{tt} in (1) results in the following expression

$$\Delta f_{tt}^3 + K_1 \Delta f_{tt}^2 + K_2 = 0 \qquad (4)$$

where

$$K_1 = \frac{f_m}{g\ell}$$

$$K_2 = \frac{-K_3}{g\ell}\left[f_m^3 - (f_m - b)^3\right]$$

$$K_3 = \begin{cases} 1.32 \times 10^2, & 2 \leq N_A \leq 6 \\ 1.05 \times 10^2, & N_A > 6 \end{cases}$$

The solution to (4) is given by

$$\Delta f_{tt} = S + T - \frac{K_1}{3}$$

$$S = \sqrt[3]{R + \sqrt{Q^3 + R^2}}$$

$$T = \sqrt[3]{R - \sqrt{Q^3 + R^2}}$$

$$R = \frac{-27K_2 - 2K_1{}^3}{54}$$

$$Q = \frac{-K_1^2}{9}$$

Finding Δf_{tt} provides B as in (2) and $(C/N_o)_B$ as in (3).

B.0 Shared Video/Radio Program Transponder

The excess relative power ratio is given by

$$\bar{r} = \frac{\left(\frac{C}{N_o}\right)_{video} + \left(\frac{C}{N_o}\right)_{radio}}{\left(\frac{C}{N_o}\right)_{video}}$$

The excess relative bandwidth ratio is given by

$$\bar{q} = \frac{18\ \text{MHz} + B_{radio}}{18\ \text{MHz}}$$

The following formulas are used for specific access modes.

B.1 SCPC-PCM/DPSK

$$\left(\frac{C}{N_o}\right)_{PCM} = \left(\frac{C}{N_o}\right)_{per\ access} + 10\log_{10}N_A + \underset{degradation}{nonlinearity}$$

$$= 67.1 + 10\log_{10}N_A + 2,\ \text{dB - Hz}$$

$$= 69.1 + 10\log_{10}N_A,\ \text{dB - Hz}$$

$$B_{PCM} = N_A \times (540\ \text{kHz}) + \text{Guard Band}$$

$$= N_A \times (540\ \text{kHz}) + 9\ \text{MHz}$$

B.2 SCPC - ΔMOD/DPSK

$$\left(\frac{C}{N_o}\right)_{\Delta Mod} = \left(\frac{C}{N_o}\right)_{per\ access} + 10\log_{10}N_A + \underset{degradation}{nonlinearity}$$

$$= 66.7 + 10\log_{10}N_A,\ \text{dB - Hz}$$

$$B_{\Delta\text{Mod}} = N_A \times (540 \text{ kHz}) + 9 \text{ MHz}$$

B.3 SCPC - FM

$$\left(\frac{C}{N_o}\right)_{fm} = \left(\frac{C}{N_o}\right)_{access} + 10\log_{10}N_A + \text{nonlinearity degradation}$$

$$= 167.92 - 20\log_{10}\Delta f_p + 10\log_{10}N_A$$

$$B_{fm} = N_a \times (\text{Carson's Rule Bandwidth per carrier}) + 9 \text{ MHz}$$

B.4 PCM/TDM/DPSK

With 2 carriers amplified by the nonlinearity there is a loss (Δ) in the resulting total output power compared with the single carrier case. The excess power required (r) is given by

$$\bar{r} = \frac{\left(\frac{C}{N_o}\right)_{video} + \left(\frac{C}{N_o}\right)_{radio}}{\left(\frac{C}{N_o}\right)_{video}}, \text{ absolute units}$$

where $\left(\frac{C}{N_o}\right)_{radio} = \left(\frac{C}{N_o}\right)_{PCM} + |\Delta|$, dB-Hz,

and Δ depends upon the relative power levels of the 2 carriers as given in Figure 5.4.

$$\left(\frac{C}{N_o}\right)_{PCM} = \left(\frac{C}{N_o}\right)_{per\ access} + 10\log_{10}N_A$$

$$= 67.1 + 10\log_{10}N_A, \text{ dB - Hz}$$

$$B_{PCM} = B_{radio} + 10\% \, (B_{video} + B_{radio})$$

$$= 1.8 \text{ MHz} + 1.1 \, B_{radio}$$

$$= 1.8 \text{ MHz} + 1.1 \, N_A \times (450 \text{ kHz})$$

B.5 ΔMod/TDM/DPSK

$$\left(\frac{C}{N_o}\right)^{*}_{\Delta \text{Mod}} = 64.7 + 10\log_{10} N_A, \quad \text{dB - Hz}$$

$$B_{\Delta \text{Mod}} = 1.8 \text{ MHz} + 1.1\ N_A \text{ x } (450 \text{ kHz})$$

B.6 FDM/FM

Values of $(C/N_o)^{*}_{FDM}$ are the same as found in A.6

$$B_{FDM/FM} = 1.8 \text{ MHz} + 1.1 \text{ B}$$

---

*These values are used in calculating $\overline{r}$ instead of $\left(\frac{C}{N_o}\right)_{PCM}$.

C.0 FM Audio Subcarriers on Video Carrier

The excess relative power ratio required to support the video and radio programs is given by

$$\bar{r} = \frac{\left(\frac{C}{N_o}\right)_{RF}}{\left(\frac{C}{N_o}\right)_{video}}$$

The $(C/N_o)_{RF}$ is the total required to support both the video and radio programs. $(C/N_o)_{RF}$ is determined as follows.

$$\left(\frac{S}{N}\right)_{video} = K + \left(\frac{C}{N_o}\right)_{RF} + 10\log_{10}(\Delta f_{video})^2, \text{ dB-Hz} \quad (1)$$

$$B = 2\left[(\Delta f^2_{video} + \Delta f^2_{radio})^{\frac{1}{2}} + f_m\right] \quad (2)$$

$$\Delta f^2_{radio} = N_A \cdot \Delta f^2_{1\ radio} \quad (3)$$

$$\left(\frac{C}{N_o}\right)_{sub\text{-}carrier} = \frac{\Delta f^2_{1\ radio}}{2} \left(\frac{C}{N_o}\right)_{RF} \cdot \frac{1}{f_{sc}^2} \quad (4)$$

where

$\left(\frac{S}{N}\right)_{video}$ = required video S/N

= constant

K = constant

$\left(\frac{C}{N_o}\right)_{RF}$ = total (C/N_o) required to support video and radio programs

Δf_{video} = peak carrier deviation due to video

Δf_{radio} = peak carrier deviation due to radio channels

$(\frac{C}{N_o})_{sub\text{-}carrier}$ = C/N_o required for a 52 dB S/N for a radio program

= 68.4 dB - Hz

B = 18 MHz

f_m = maximum video frequency

= 4.2 MHz

f_{sc} = audio sub-carrier frequency

= 6.8 MHz

Using (2) - (4) in (1) and recognizing that $(C/N_o)_{RF}$ = 86.6 dB - Hz (DBS requirement) for $N_A = 0$ yields

$$(\frac{C}{N_o})_{RF} = a\log_{10}(8.66) + 2.78 \times 10^7 N_A, \text{absolute units}$$

C.1 FM Audio Sub-Carriers Only on an FM Carrier

$(C/N_o)_{RF}$ is the total C/N_o required to support N_A FM audio sub-carriers one FM carrier. The equations applicable to this case are as follows:

$$\frac{C}{N} = \frac{1}{B} (\frac{C}{N_o})_{RF}$$

$$= 14 \text{ dB} \tag{1}$$

$$B = 2\left[\Delta f_{radio} + f_m\right] \tag{2}$$

$$\Delta f_{radio} = \begin{cases} N_A \cdot \Delta f_{1radio}, & N_A < 10 \\ \sqrt{N_A} \cdot \Delta f_{1radio}\, \bar{p}_k, & N_A \geq 10 \end{cases}$$

$$f_m = (100 + 200\, N_A) \times 10^3, \quad \text{Hz} \tag{4}$$

$$\left(\frac{C}{N_o}\right)_{\text{sub-carrier}} = \frac{\Delta f_{1radio}^2}{2} \left(\frac{C}{N_o}\right)_{RF} \cdot \frac{\bar{W}}{f_m^2} \tag{5}$$

where

Δf_{radio} = peak carrier deviation due to radio sub-carriers

Δf_{1radio} = peak deviation due to sub-carrier at f_m

f_m = maximum baseband frequency of sub-carriers

$\left(\frac{C}{N_o}\right)_{\text{sub-carrier}} = \frac{C}{N_o}$ required for a 52 dB S/N for a radio program

$= 68.4$ dB - Hz.

p_k = peak-to-rms voltage ratio for audio sub-carrier

$p_k = 20 \log_{10} \bar{p}_k$

$= 10$ dB.

W = pre-emphasis weighting factor

$$= 10 \log \overline{W}$$

$$= \begin{cases} 3 \text{ dB}, & 2 \leq N_A \leq 6 \\ 4 \text{ dB}, & N_A \geq 6 \end{cases}$$

By using equations(1)-(4) in (5) an expression for Δf_{1radio} as a function of N_A is obtained from which $(C/N_o)_{RF}$ and B can be obtained as a function of N_A. Values of $(C/N_o)_{RF}$ and B are used to derive power and bandwidth efficiencies for two cases:

Case 1 - Separate Dedicated Transponder

$$\left(\frac{C}{N_o}\right)_{radio} = \left(\frac{C}{N_o}\right)_{RF} + \text{nonlinearity degradation}$$

$$= \left(\frac{C}{N_o}\right)_{RF} + 1, \text{ dB-Hz}$$

$$r = \frac{(C/N_o)_{radio}}{(C/N_o)_{video}}$$

$$= \frac{\left(\frac{C}{N_o}\right)_{radio}}{4.57\text{x}10^8}$$

$$q = \frac{B_{radio}}{18 \text{ MHz}}$$

Case 2 - Shared Transponder (video FM carrier, radio FM carrier).

With 2 carriers amplified by the non-linearity there is a loss (Δ) in the resulting total output power compared with the single carrier case.

$$\bar{r} = \frac{(\frac{C}{N_o})_{video} + (\frac{C}{N_o})_{radio}}{(\frac{C}{N_o})_{video}} \quad \text{,(abs. units)}$$

where

$$(\frac{C}{N_o})_{radio} = (\frac{C}{N_o})_{RF} + |\Delta|, \text{ dB - Hz.}$$

Δ is based on the relative power levels of video and radio carriers and is derived from Figure 5.4 according to:

$$\frac{P_{radio}}{P_{video}} = \frac{(C/N_o)_{RF}}{(C/N_o)_{video}}$$

For the excess bandwidth ratio

$$B_{radio} = 1.8 \text{ MHz} + 1.1B$$

$$q = \frac{18 \text{ MHz} + B_{radio}}{18 \text{ MHz}}$$