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THE DESIGN AND DEVELOPMENT OF A SCPC DIGITAL RADIO PROGRAM RECEIVE

PHASE I

TASK II - SYSTEM DEFINITION

MCS MILLER COMMUNICATIONS SYSTEMS LTD.

THE DESIGN AND DEVELOPMENT OF A SCPC DIGITAL RADIO PROGRAM RECEIVER
PHASE I
TASK II - SYSTEM DEFINITION

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1.0 INTRODUCTION

The SOW regarding the system definition task of phase I requires the definition of the system parameters and overall design specifications for the receiver which includes the demodulator, error correction decoder, demultiplexer, and source decoder. In order to evolve an efficient cost effective system design, it is important to consider various aspects such as the user environment, the transmission impairments, and the technology. Some of these are briefly discussed before a particular design is proposed.

As the system definition task was carried out in parallel with market survey, the conclusive results of the market survey could not be used at the time of the preparation of this report. Further, the relative merits of different coding and modulation techniques are to be assessed in detail in Phase II of this program.

Section 2 of this report deals with the system analysis. This includes transponder characteristics, existing earth station facilities, network distribution strategy, interference including intermodulation, fade margin, link calculation, etc.

Section 3 deals with the system design concept in which a basic system is defined schematically. Following this, the various distribution configurations in which the proposed system can be used are analysed. System interface requirements as dictated by the backhaul links and the consequent constraints on the subsystem design are outlined. Various subsystem design concepts are also discussed.

2.0 TRANSMISSION SYSTEM ANALYSIS AND SPECIFICATIONS

The receiver may be operated in a variety of transmission environments using different satellites. In the North American scenario, the C-Band satellites which are currently being used or planned for the use of radio program distribution include ANIK, SATCOM, WESTAR, COMSTAR, etc. Although the characteristics of the C-Band transponders of these satellites are roughly similar, the receiver performance can vary significantly depending on the beam coverage, earth station location, interference environment, etc.

The use of ANIK satellites for the radio program distribution is studied in some detail in the following sections. The problems considered include transponder characteristics, interference, EIRP contours, fade margin, link budget, frequency control, etc.

2.1 Anik-D Transmit And Receive Patterns

In Canada, the prime radio and TV network viz., CBC, uses both satellite and terrestrial networks for the distribution of the programs. The satellite distribution is primarily done in C-band using Telesat's Anik satellites. The EIRP contour of a typical Anik satellite viz., Anik-D, is given in Figure 2.1. The satellite EIRP providing all-Canada coverage is 36 dBW for both horizontally and vertically polarized signals. If required, Anik-D satellite reflectors may be tilted south to give better coverage of the continental U.S.A. The typical 6 GHz G/T receive pattern is shown in Figure 2.2.

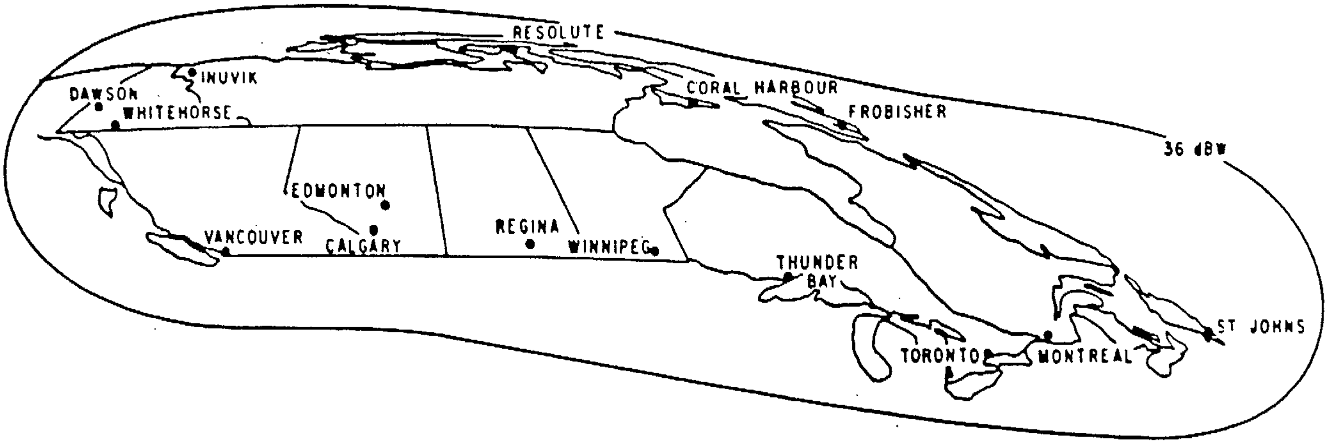


Fig. 2.1 ANIK D 4 GHz TRANSMIT PATTERN (EIRP) TYPICAL HORIZONTALLY POLARIZED

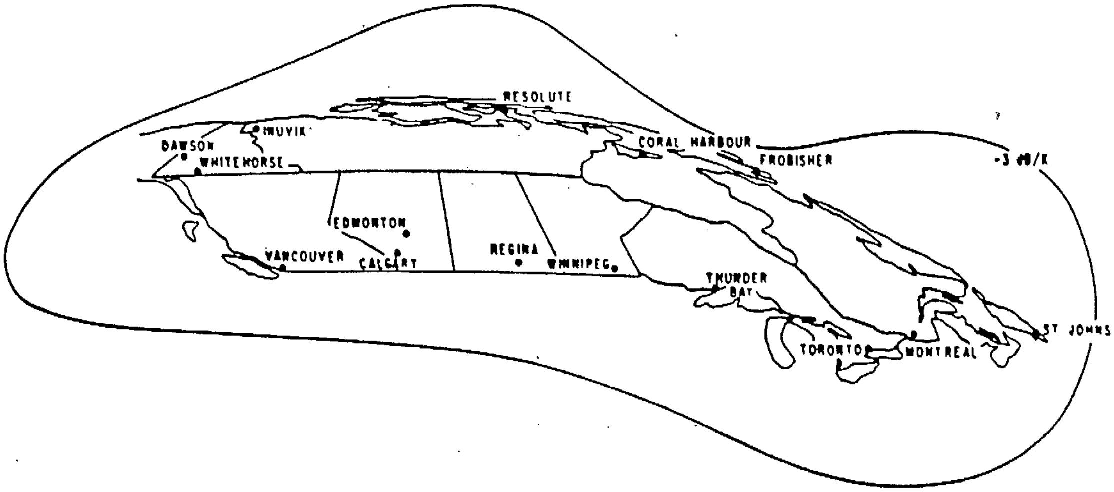


Fig. 2.2 ANIK D 6 GHz RECEIVE PATTERN (G/T) TYPICAL HORIZONTALLY POLARIZED

2.2 Existing Earth Station Facilities

At present, the CBC's radio and TV program distribution is accomplished using a patchwork of links involving microwave, land lines and satellite. The transmit and receive earth station facilities are owned by Telesat. There are, however some CBC owned receive only earth stations which can receive TV and sub-carrier audio. Depending on the location and service requirements, Telesat's C-Band earth stations have G/T ranging from 18.5 to 37.5 dB/K. Telesat's existing earth station types at 6/4 GHz for TV and Radio distribution are given in Table 2.1.

Figure 2.3 shows the location of Telesat's Television and Radio earth stations as of 1982.

2.3 Networks' Distribution Strategy

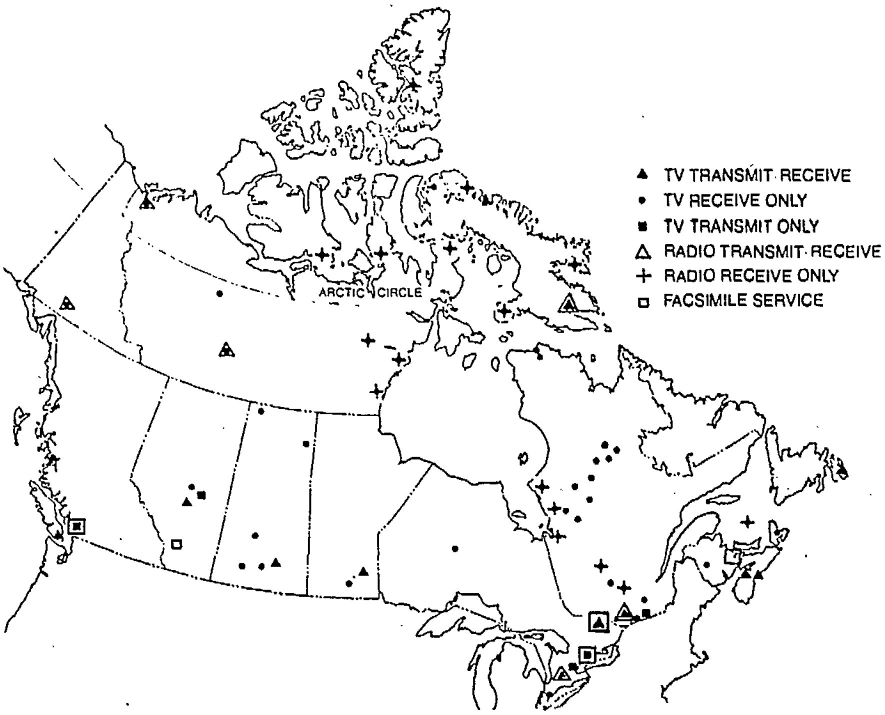
In general, Radio Networks' distribution strategy will be influenced by, among other things, the need for upgraded services, technology, new service requirements and the overall short-and-long term economics.

It is clear that CBC is willing to upgrade the service and change the distribution approach within their short term economic constraints. However, there doesn't seem to be any positive indication that CBC is keen on employing new technology or providing many new services. Based on the obvious advantages of network growth, service changes and operational conveniences, CBC sees that satellite distribution will be more economical to serve its 457 distribution points and 32 production centers. (The figures are not official). The satellite envisioned in this case is Anik D. The CBC's switchover to satellite

Earth Station Type	Antenna Diameter (m)		G/T (dB/K)
Network TV (Transmit & Receiver)	A B	30 10	37.5 28.0
Northern TV (Transmit Only)	A B	11 8	N/A N/A
Remote TV (Receive Only)	A B C	8 8 4.5	26 22 21.5
Frontier TV (Receive Only)	A B	4.5 3.6	18.5 18.5
Transportable TV (Transmit/Receive)	A B	4.5 4.5	N/A N/A
Facsimile			
Transmit		8.0	N/A
Receive		4.5	N/A

Table 2.1:

Figure 2.3 6/4 GHz Television & Radio Service Locations 1982



distribution will neither be abrupt nor complete. However, this process may be speeded up if the satellite rental tariffs and the earth station costs do not spiral up.

Considering satellite distribution, there are five feasible modes of operation;

(1) Sub-carrier of a TV signal,

(2) SCPC at the band-edge of a TV transponder,

(3) SCPC in a dedicated (homogeneous) transponder,

(4) SCPC in a heterogeneous transponder

(5) Multiplexed channels on a single carrier transponder.

The sub-carrier approach has some disadvantages viz., (1) since the radio signal has to always accompany the TV, the timing and duration of these two services may not favour the existing traffic situation, (2) all the radio programs have to be collected at the TV uplink station using other links, and (3) the radio program is essentially meant for distribution to locations that are equipped with suitable TVRO's. The major advantage of this approach is that relatively inexpensive add-on equipment is needed for the radio distribution.

In the case of SCPC carriers sharing the edge of a TV transponder, there is no additional transponder cost. Also, the receiver can operate with some minimal add-on units to the existing receive earth stations. The problems of operating SCPC carriers at the edge of the band of a transponder designed primarily for the needs of TV have to be carefully evaluated. The intermodulation interference limits will require that the SCPC carriers are operated at a very low level. The operational suitability of this approach using a low cost receiver in a Canadian scenario is yet to be demonstrated. Further, the number of channels available on a TV transponder may not be sufficient for the network needs.

The configuration of multiplexed channels on a single carrier will utilize transponder power more efficiently as compared to the SCPC mode. However the SCPC approach has several advantages over the former,

(1) easy terrestrial link compatibility.

(2) easy initial network implementation and subsequent growth.

(3) separate carriers afford privacy and independent programming schedules.

(4) multiple uplink origination locations possible.

(5) links with transmit facility can also be used for back hauling programs.

Thus, the SCPC approach is uniquely attractive to both small and medium networks as well as large networks with multiple origination locations. Service economy, operational and growth flexibility and network privacy are some of the assets of the SCPC approach.

However, the choice of operating SCPC in a homogeneous mode (all SCPC carriers in a transponder are of the same type) or in a heterogeneous mode (SCPC carriers sharing a transponder with other modulation type, low and medium bandwidth carriers) essentially depends on the traffic requirements and transponder availability. In either case optimum utilization of transponder power (and possibly bandwidth) is necessary and will have to be studied by the carriers (e.g. Telesat) in their own interest.

As far as Radio Networks are concerned, if going for satellite distribution is the first step, and choosing SCPC is the second step, then there is an important third step as to decide which technology (digital or analog) is appropriate. The advantages of digital technology as compared to analog are obvious in regard to program quality, transmission channel immunity and additional new service capability. The question of the number of carriers per transponder is interesting. While a typical Anik-D type transponder can deliver about 23 mono (15 kHz) channels using analog (FM) technology, the same transponder can be used to handle about 15 stereo digital carriers (dual 15 kHz channels plus 32 kb/s data) using receiver earth stations with comparable G/T. This appears to be possible using powerful FEC codecs providing a coding gain of up to 5 dB (otherwise about 8 carriers with 2.5 dB FEC coding gain). Further, a power advantage of about 3 dB per carrier is available for digital carriers since there are twice as many carriers required in analog transmission for the same number of program channels. A similar advantage (a factor of two) can be seen in the number of receivers for the digital SCPC carriers. This will reflect in the equipment cost per program channel. Further, the smaller bandwidth occupancy of an analog carrier is not a practical advantage as most of the transponders are power limited.

2.4 Interference

The interference models for the overall link are discussed in Appendix A. The specific values of interference levels corresponding to Anik-D are provided in the following Table 2.2. These values are based on the information from [1]. The homogeneous multicarrier operation is considered.

2.5 Transponder Utilization Versus Intermodulation

The various ways that a transponder can be utilized versus the relative intermodulation advantages are discussed in Appendix B. The methods of evaluating the intermodulation interference for both homogeneous and heterogeneous multicarrier operation are also briefly discussed in Appendix B.

2.6 Fade Margin

Generally, the variation in the overall receive level is caused by a number of time-varying random processes. These include:

- up-and-downlink rain fades
- atmospheric absorption
- antenna pointing errors
- transmitter power variations

The overall margins required for a satellite link depend on the system availability. When the transponder is operated in a single carrier saturation mode such that any fade on the uplink does not pull the transponder out of saturation, the uplink fade margins can be neglected.

The largest of these fades occur due to rain. This is a function of rain rate, earth station elevation angle and vertical depth of rain cells.

Source	Symbol	C/I (dB-Hz)
Cross-polarization (uplink)	$(C/I_o)_{XU}$	$-B_i+109$
Cross-polarization (downlink)	$(C/I_o)_{XD}$	$-B_o+104$
Adjacent Satellite	$(C/I_o)_{ASU}$	$-B_i+103$
Adjacent satellite	$(C/I_o)_{ASD}$	$\mathrm{EIRP}-B_o+(13+G_e{}^*)$
Intermodulation (uplink)	$(C/I_o)_{IMU}$	$-B_i+101$
Intermodulation (downlink)	$(C/I_o)_{IMD}$	$-B_o+93$
Terrestrial	$(C/I_o)_T$	x

*receive boresight gain of the earth station antenna

B_i - refers to the satellite input backoff

B_o - refers to the satellite output backoff

x - depends on earth station location

Table 2.2

However, for the multicarrier operation, the transponder is operated in an almost linear region with large backoffs. The uplink fades in this case are directly added to the link calculations. The details of rain fades and antenna pointing errors are discussed in Appendix C. The breakdown of the total fade margin for 99.99% availability is given below.

Parameter	Margin (dB)
rain fade	1.3
atmospheric absortion	0.2
antenna pointing loss	0.1
transmit power variation	0.2
Total fade margin	1.9 dB

2.7 Link Budgets

The link calculations provided below correspond to the Anik-D satellite providing coverage to the whole of Canada. The interference and the backoff levels assumed in the calculation are as per [1]. A typical receive earth station is assumed to provide a G/T of about 17.3 dB with a 3m antenna and a 120°K LNA. In this calculation it is assumed that the transponder operates in a homogeneous mode handling 7 digital SCPC carriers.

Parameter	Unit	Value
Uplink EIRP	dBW	65.6
Uplink path loss	dB	200.1
Boltzmann's Constant	dB	228.6
Satellite G/T	dB/K	-3.0
Additional Losses	dB	0.2
$(C/N_o)_{up}$	dB-Hz	90.9

Composite $(C/I_o)_{uplink}$	dB-Hz	81.0
Net uplink (C/N_o)	dB-Hz	80.6
Saturated Downlink EIRP	dBW	36
Multicarrier Backoff	dB	13
Downlink EIRP (per carrier)	dBW	23.0
Downlink Path Loss	dB	196.2
Earth Station G/T	dB/K	17.3
Additional Losses	dB	0.3
$(C/N_o)_{down}$	dB-Hz	72.4
Composite $C/I_o)_{down}$	dB-Hz	73.9
Net downlink (C/N_o)	dB-Hz	70.1
Overall link C/N_o	dB-Hz	69.7
Fade margin (99.99%)	dB	1.6*
Information bit rate (800 kbs)	dB	59
Available E_b/N_o	dB	9.1
Required E_b/N_o for BER=10^{-7}) (with FEC of coding gain 5 dB)	dB	6.3
Implementation loss	dB	2.5
Extra margin	dB	0.3

Detailed link calculations are given in Appendix C. Additional margins can be obtained by increasing the receiver G/T.

2.8 Transponder Capacity: FM Versus Digital

The number of digital SCPC carriers per transponder is provided against available E_b/N_o for different G/T values in Figure 2.4.

This calculation was done for the Anik-D satellite and the proposed digital SCPC system. The digital SCPC system carries two 15 kHz mono channels plus one 32 kbps data.

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*Clear weather atmospheric absorption losses are included under the additional losses.

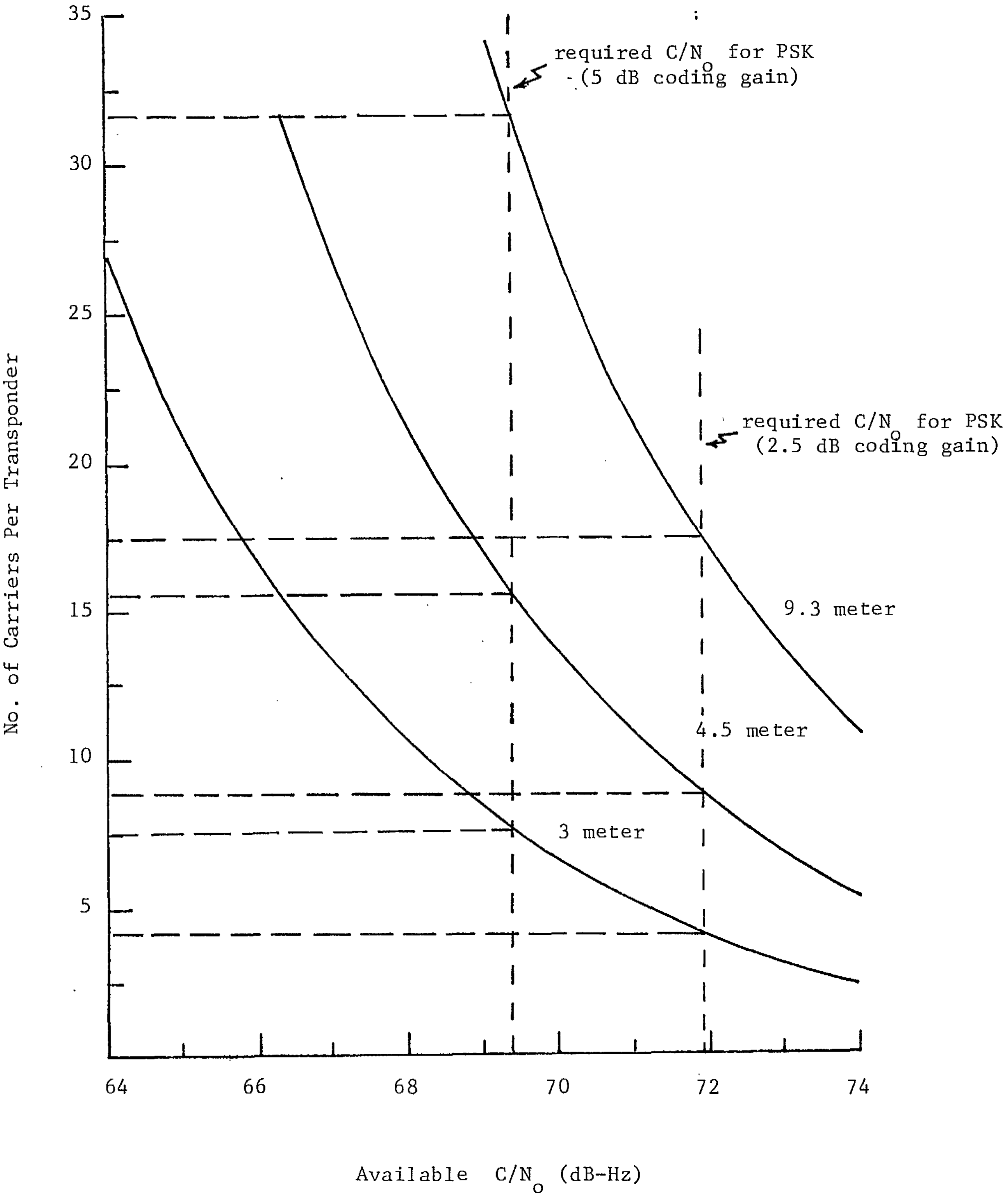

Figure 2.4 No. of Digital Carriers per Transponder (NOTE: 1 digital carrier contains 2 15 KHz mono channels)

The numbers 3m, 4.5m, and 9.3m represent antenna diameters with an LNA of 120° K. The vertical dotted lines correspond to the C/N_o required for the digital SCPC receiver to achieve a BER of 10^{-7}. One of the lines corresponds to an FEC codec with a coding gain of 2.5 dB and the other to an FEC codec with a coding gain of 5 dB.

For the same transponder and earth station G/T link, the number of analog FM SCPC carriers is given in Figure 2.5. One FM SCPC carrier provides one 15 kHz mono channel. The vertical dotted line correspond to the C/N_o requirement for Wegener's 'Panda' FM SCPC equipment (Series 1600). This requires (from quoted specs) an operational C/N_o of 66 dB-Hz. An additional fade margin of 1.6 dB is added to the required C/N_o. A comparison between the number of carriers per transponder between digital and FM SCPC is provided in Table 2.3.

These calculations suggest that the digital SCPC with moderate gain (2.5 dB) FEC will deliver a lower number of program channels per transponder than the FM SCPC, and the digital SCPC with high coding gain (5 dB) will deliver more channels per transponder than the FM SCPC.

2.9 SCPC at The TV Band Edge

The idea of the use of SCPC carriers at the band edge of a TV transponder is attractive since no additional space segment cost is involved when the transponder is already leased by the TV user. The problem of mutual interference has been studied in some detail in [2]. This and other studies suggest that,

- the TV carrier center frequency (f_{TV}) should be near the center of the transponder so that the intermodulation interference doesn't significantly affect the adjacent transponder,

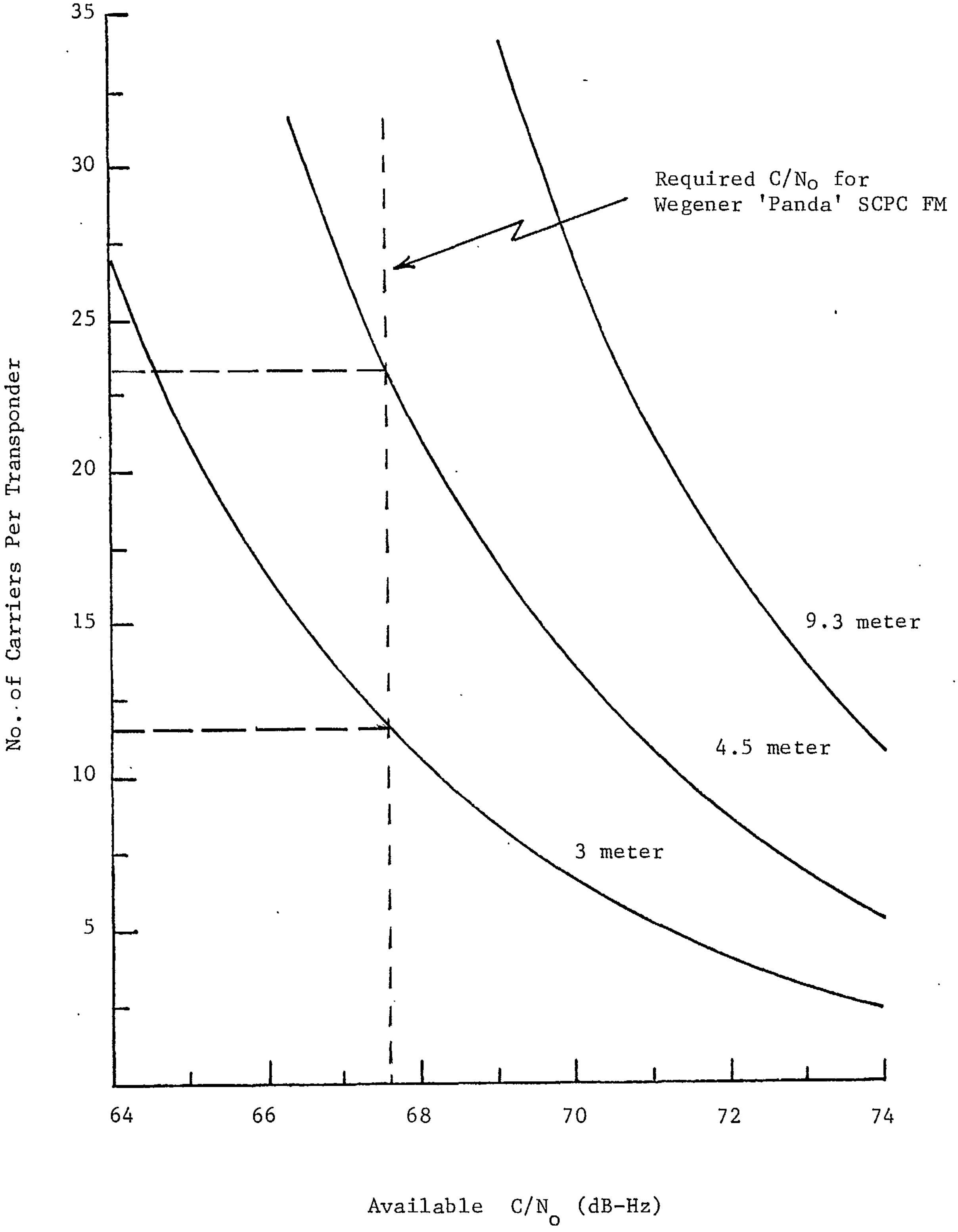

Figure 2.5 No. of Analog SCPC Carriers per Transponder (NOTE: 1 analog carrier contains 1 15 KHz mono channel)

Antenna Diameter LNA → 120°K	Number of Carriers Per Transponder		
	Digital SCPC		FM SCPC
	FEC Gain: 2.5 dB	FEC Gain: 5 dB	
3m	4	7	11
4.5m	8	15	23
9.3m	17	31*	--

One digital SCPC contains 2 15 kHz mono plus one 32 kbs data.
One FM SCPC contains one 15 kHz mono.
*Transponder may become bandwidth limited depending on the type of modulation and the FEC code rate used.

Table 2.3: Number of Carriers per Transponder: digital SCPC versus FM SCPC.

- the radio carriers must be grouped one side of the TV carrier since the power levels of the $(2f_{TV}-f_R)$ IM products are comparable to those of the radio carriers (f_R),

- the radio and TV carriers should be separated by a guard band (at least equal to radio carrier bandwidths) in order to avoid the $f_{TV} + f_{R1} - f_{R2}$ type IM products falling into the radio program, and

- the radio SCPC carriers should be about 17 to 20 dB below the TV level in order to ensure that the TV degradation due to interference is within the acceptable limits.

A typical C/N_o required to achieve a BER of 10^{-7} using the proposed digital SCPC system is about 67.8 dB-Hz. This includes an implementation margin of 2.5 dB.

The operational C/N_o required for a typical FM SCPC system (Wegener - 'PANDA' series 1600) is 66 dB-Hz. Assuming an SCPC carrier is placed at the bandedge of a TV transponder at a level about -18 dB compared to the TV signal level, a link calculation performed taking into account typical noise levels and fade margins reveals that a "3m - 120°K" earth station receiver (G/T = 17.3) will not be able to provide enough C/N_o for either of the technology (digital or FM). Under best link conditions (minimum noise, interference, and fade) C/N_o may be just sufficient. However, if the receiver uses a 4.5m antenna and 120°K LNA ($G/T \approx 22$ dB) then there will be enough C/N_o for digital SCPC or FM SCPC.

3.0 SYSTEM DESIGN CONCEPTS

3.1 Overall Radio Program Distribution Concept

The schematics of an overall radio program distribution system is shown in Figure 3.1. The basic system will accept program audio and data inputs at the network studio and distribute them to the affiliates. The data streams are multiplexed in T1 format and transmitted through a terrestrial T1 link to the uplink earth station. At the transmit earth station the T1 format data is demultiplexed and remultiplexed in a channel multiplexer. The resulting bit stream is FEC coded, modulated and transmitted to the satellite. Generally, the terrestrial links and the transmit uplink services are provided by common-carriers. At the network studio a local receiver is used to receive the satellite output. This is demodulated and decoded and used for monitoring purposes.

At the network affiliated station, the data stream is received from the satellite and demodulated, decoded and converted to analog program signals. It is also possible that the data stream received by the network-affiliate may be transmitted to another destination through a T1 link before D/A conversion. In this case the channel demux output has to be processed in a T1 link mux before transmission through a T1 link.

Transmit earth stations may have the capability to uplink more than one carrier and a local monitor. Additionally, programs coming from remote feeds that don't require editing at network studio can be directly linked to the transmit earth station input via a T1 link. In this case there may also be a direct T1 link from the earth station to the network studio for monitoring purpose.

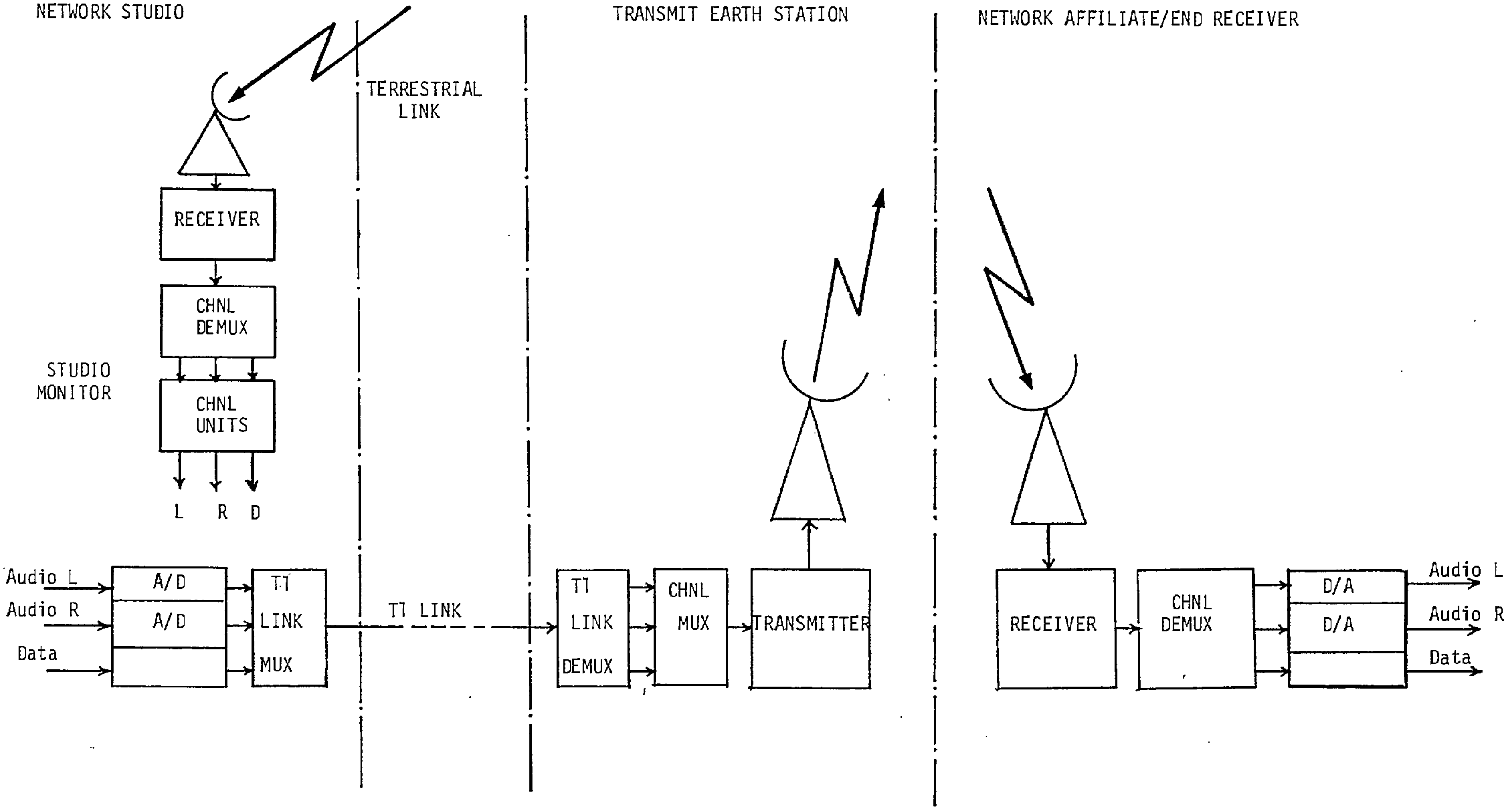

Fig. 3.1. Overall Radio Program Distribution System Concept

Figure 3.1 does not show the standby units which are used to increase the overall system reliability.

3.2 Basic System Configuration

A basic digital audio program receiver system is schematically shown in Figure 3.2. A typical receive station will have a 3m antenna and a 120°K LNA. The 4 GHz at the LNA output will be double-down converted to a 70 MHz centre frequency. Depending on the particular demodulation process implemented, the frequency and phase of the carriers will be tracked. After demodulation, the regenerated output data stream will be passed through an FEC decoder to correct most of the corrupted bits. The error corrected data will be demultiplexed using the frame sync information. The channel bit streams are analog converted to recover the program audio. In order to suppress the subjective effects of uncorrected but detected errors, error concealment and muting techniques are employed. The receiver is normally provided with frequency agility through a programmable synthesizer.

A complementary transmitter system is shown in Figure 3.3. The transmitter earth station is generally provided with an antenna system having larger G/T. The frequency agility is incorporated in the transmitter.

3.3 Source Codec

Block diagrams of the 15 kHz source encoder and decoder are shown in Figure 3.4. The technique used is instantaneously companded (14 bits to 11 bits) PCM. With the addition of one parity bit, a twelve bit word is generated for each sample. The A-law companded PCM technique is recommended

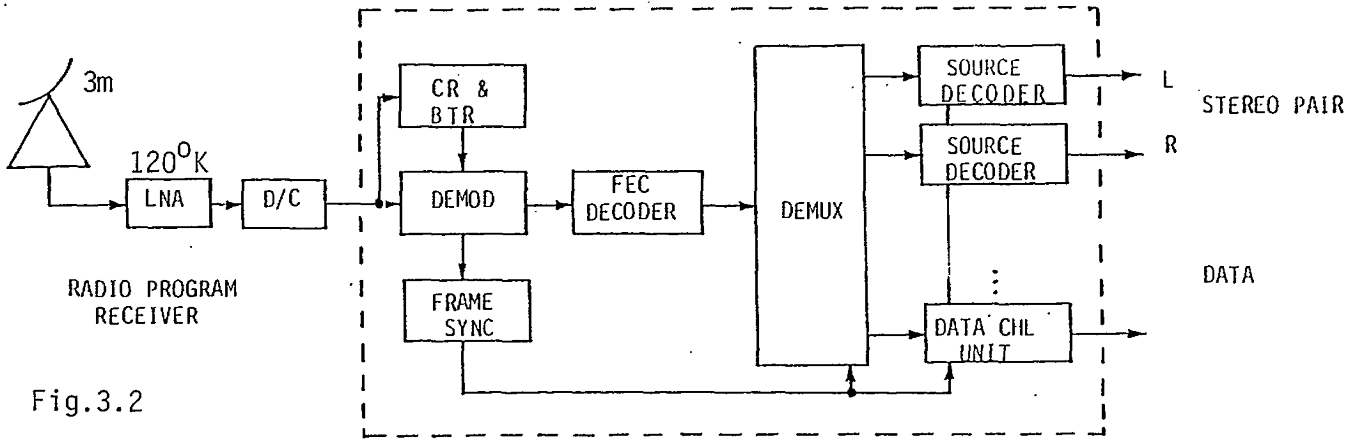

Fig.3.2

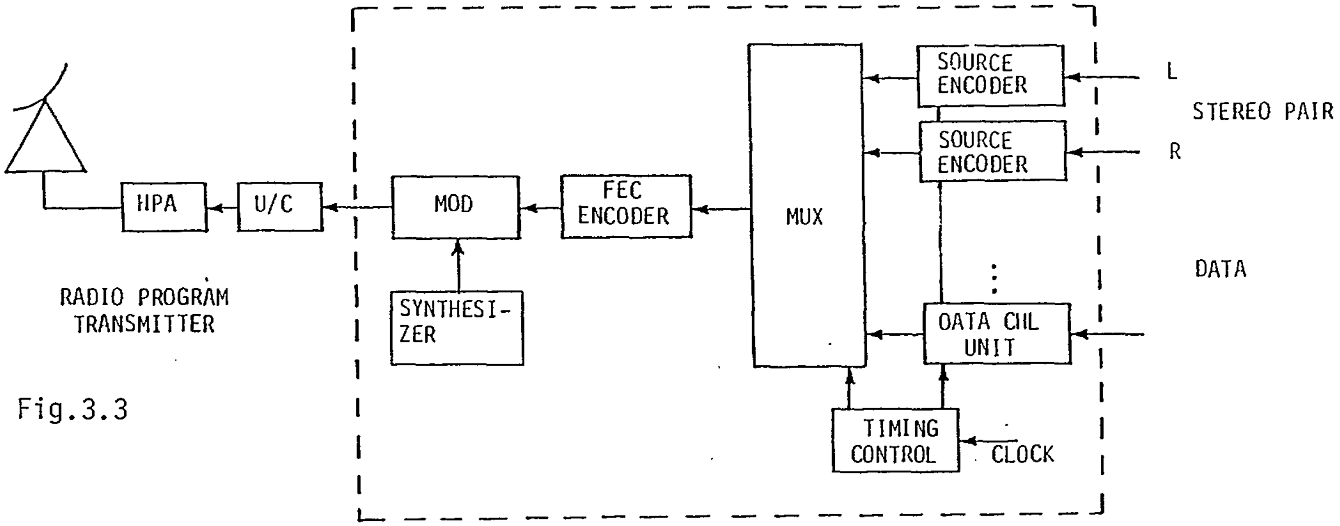

Fig.3.3

Overall Block Diagram of Radio Program Receiver and Transmitter

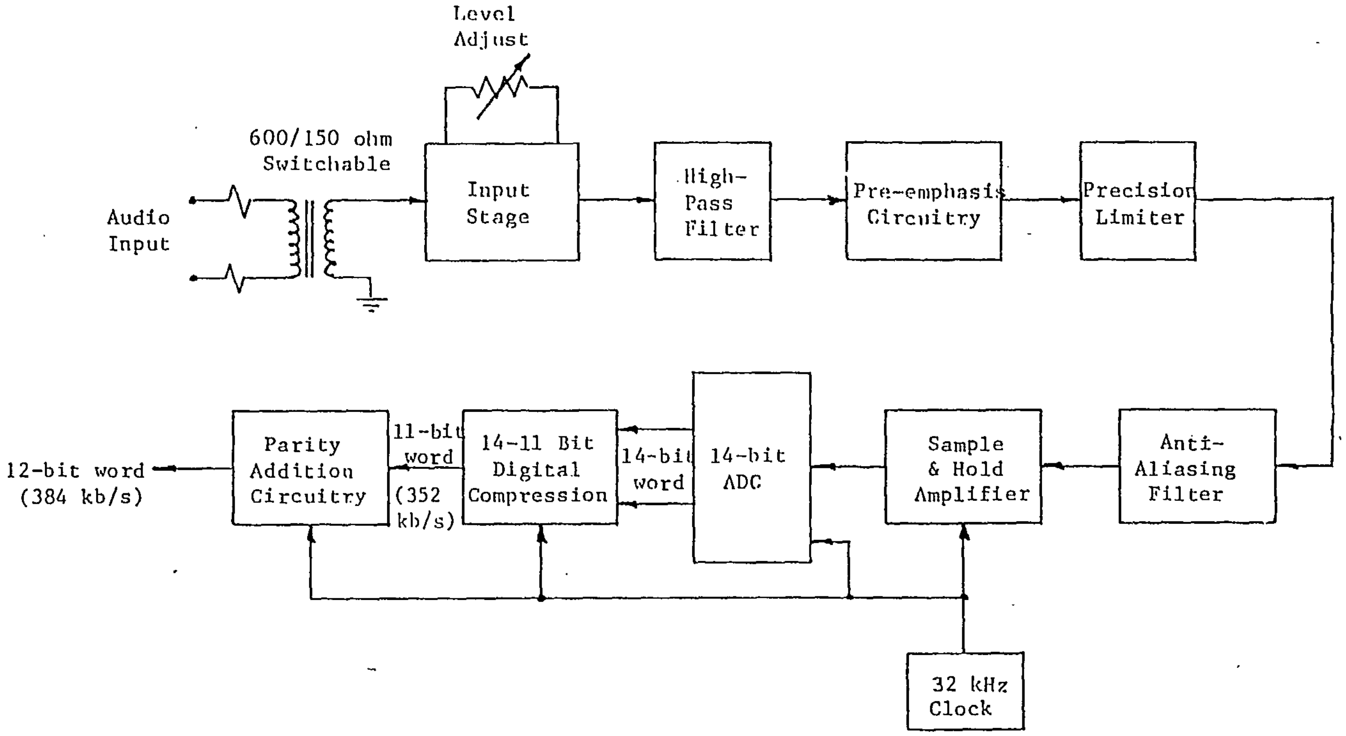

Figure 3.4a Source Encoder Block Diagram

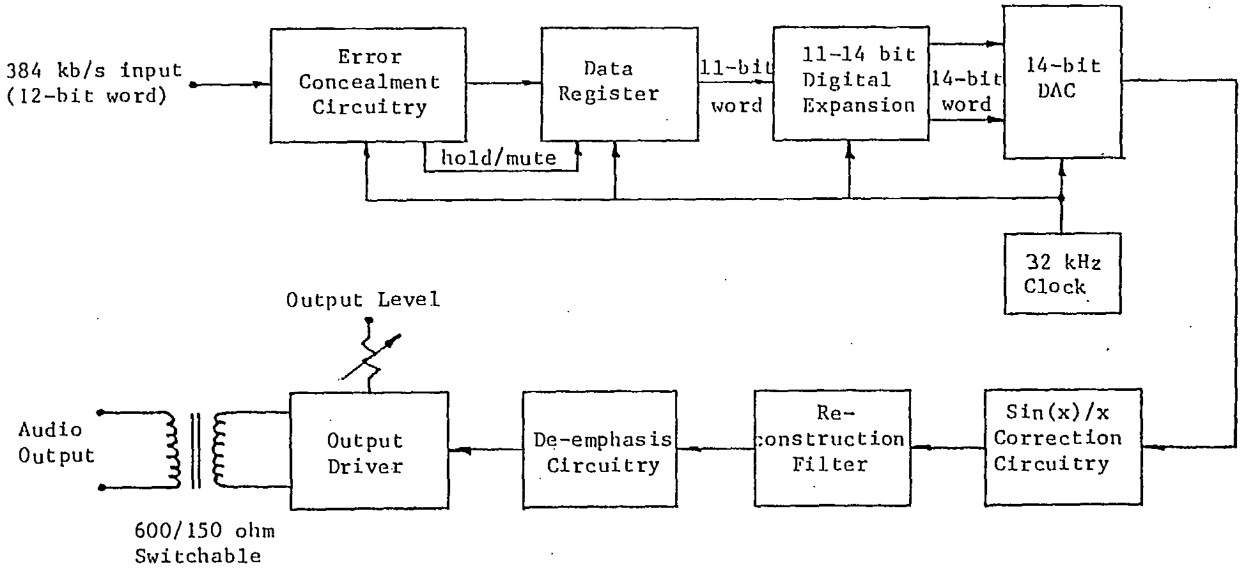

Figure3.4b Source Decoder Block Diagram

by CCITT. The relative performance of this technique as compared to others will not be discussed in detail here. The implementation advantages are:

- relatively simple source codec implementation

- conversion of one 15 kHz channel into two 7.5 channels can be done readily

- multiplexing of program channels with data channel is straightforward

- forward error correction (FEC) can be introduced on the overall multiplexed bit steam and the FEC codec can be implemented in an independent modular form

- direct conversion between different companding characteristics (e.g. A-law to μ-law) is possible.

The codec corresponding to a 7.5 kHz audio channel can be implemented using the same technique as in Figure 3.4, but now the sampling frequency becomes 16 kHz and the filter cut-off frequencies are appropriately reduced.

An alternative to the dedicated codec is the 'shared codec' concept shown in Figure 3.5. In this implementation all the audio channels share one set of digital processing units viz., A/D converter, 14-11 bit compressor, parity coder etc. There are several disadvantages in this approach:

- although converting two 15 kHz channels into four 7.5 kHz channels is relatively simple, it is not easy to convert one 15 kHz channel into two 7.5 kHz channels while retaining the other as a 15 kHz channel.

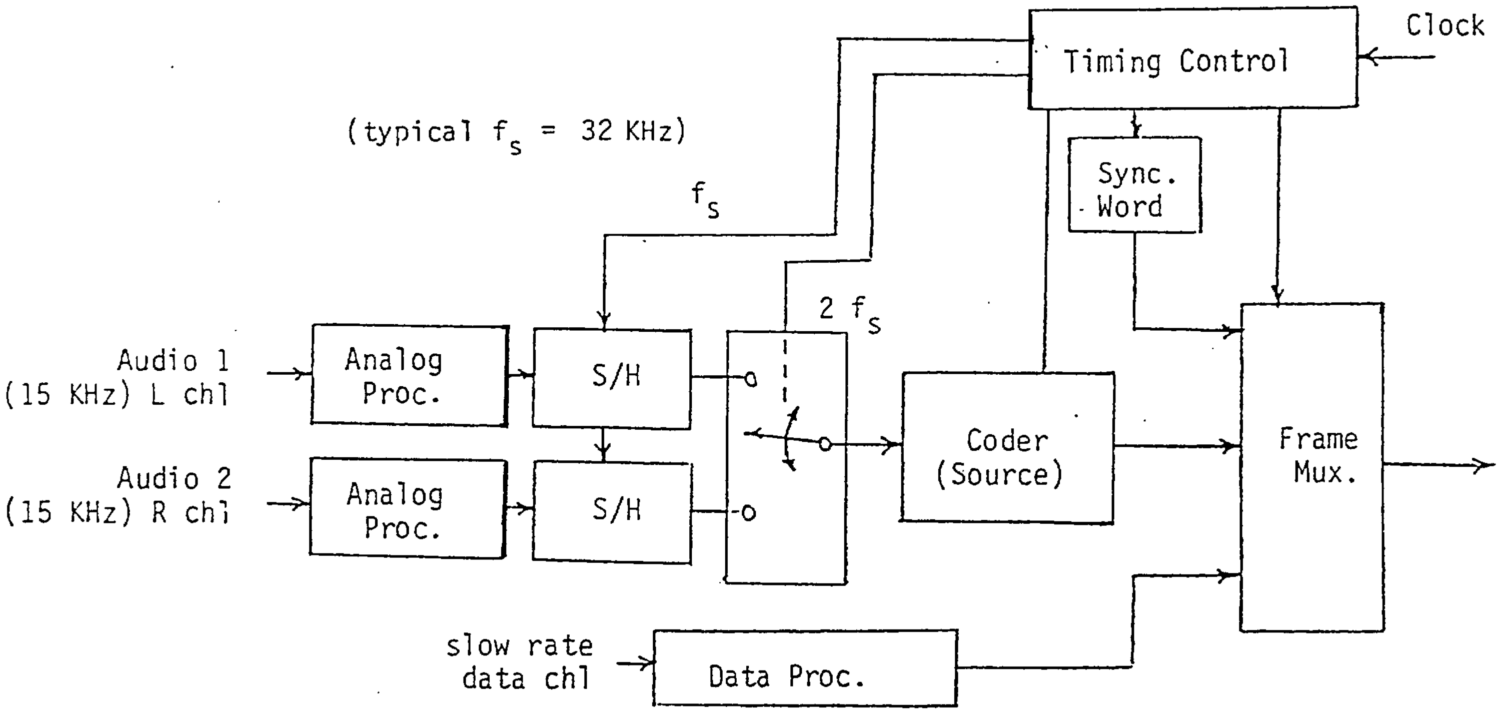

Fig. 3.5 'Shared' codec

- providing additional data capability in part of the audio channels will pose implementation complexities.

- additionally, commercial codecs are available only in the dedicated codec configuation as shown in Figure 3.4.

Therefore the dedicated codec technique as shown in Figure 3.4 is considered the preferred approach.

3.4 Mux - Demux

The design of multiplexer and demultiplexer are important from the system flexibility point of view. Figure 3.6 gives the configurations of a simple multiplexer and demultiplexer. The channel multiplexer and demultiplexer shown in Figure 3.6 will directly interface with the earth station transmit and receive equipments.

Additional T1 link mux - demux units are required to link the data stream from the studio center to the transmit earth station via a T1 link. This is shown in Figure 3.7. The studio produced digitized audio and data are combined in a T1 link mux which directly interfaces with the T1 link data format. At the earth station the T1 link demux segregates the input data into constituent bit streams. The channel mux following this interfaces with the satellite uplink. The process is exactly the reverse for the earth station to studio link.

A program receiver will use configuration 3.6b. The prototype system will implement only the channel mux-demux configuration. The networks or affiliates who need to use a T1 link can develop or buy a T1 link mux and a T1 link demux. However what is important here is to design the channel mux - demux to handle exactly the same input formats as a T1 link mux.

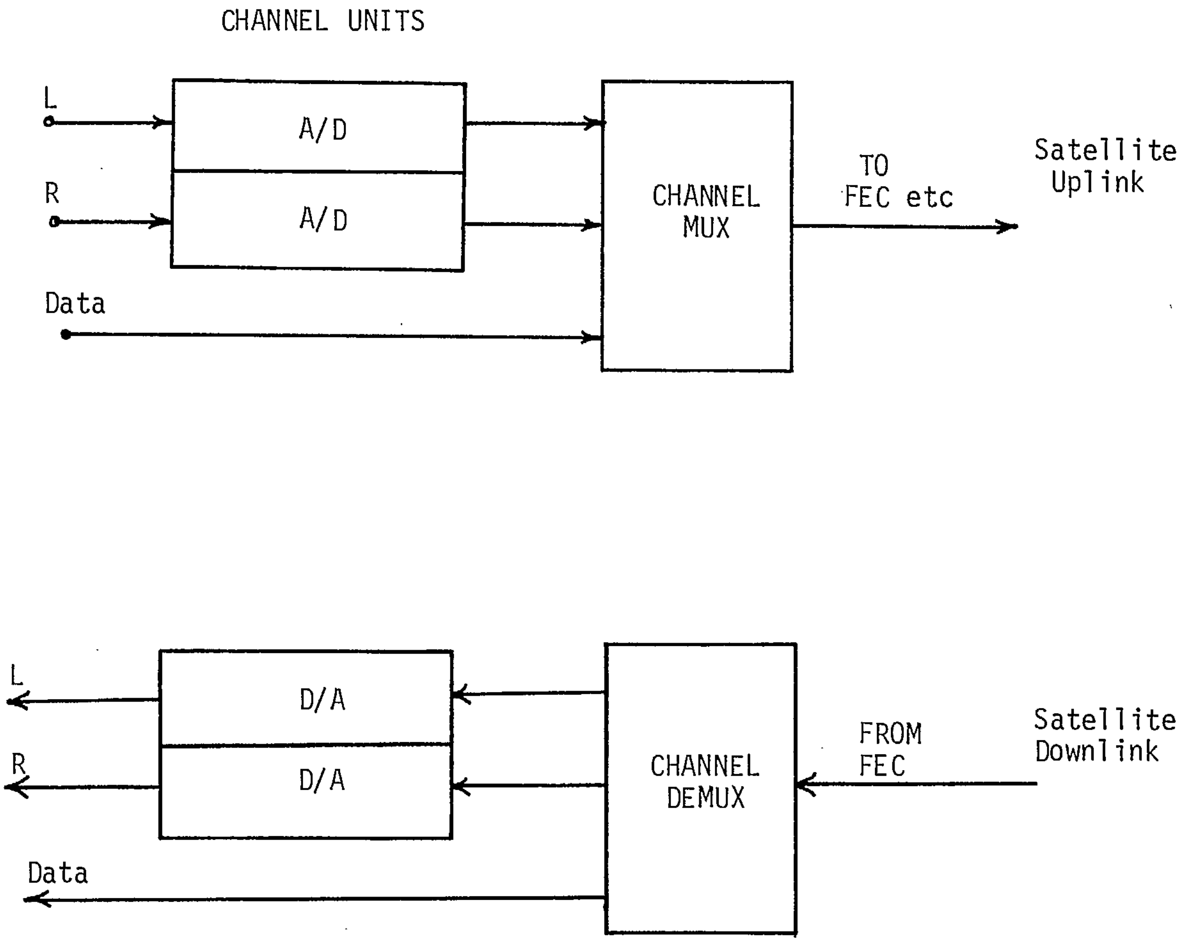

Fig. 3.6 Channel Mux and Demux Directly Interfacing with Satellite Links

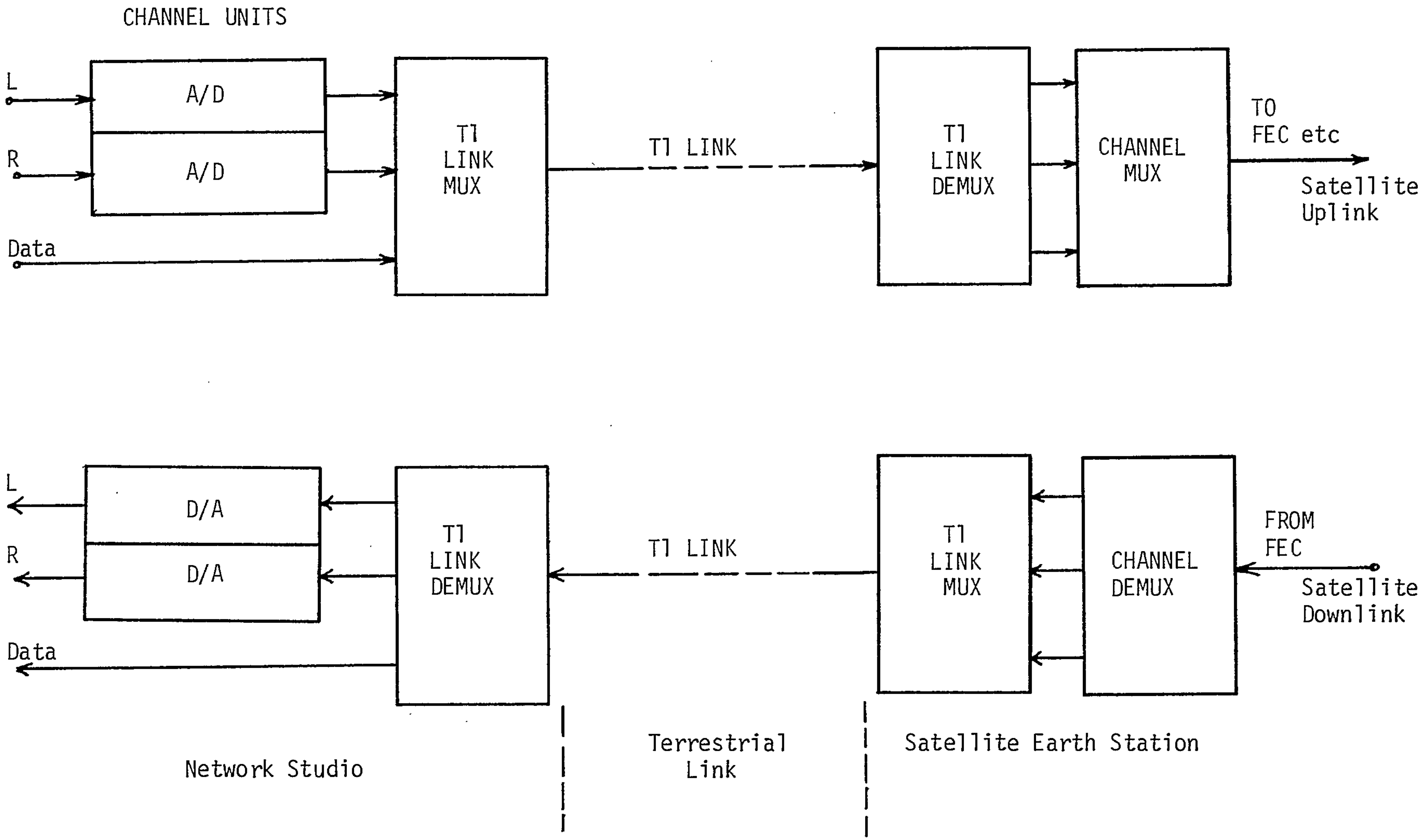

Fig. 3.7 Channel Mux and Demux Interfacing with Satellite Link Through T1 Link mux and T1 Link Demux

3.5 FEC Codec

The application of forward error correction (FEC) techniques to achieve power gain appears to be very important. The multiple carriers accessing a single transponder operate in a power limited mode. Therefore it is necessary to use FEC to achieve as much coding gain as possible. As an initial consideration, coding technique offering coding gains from 2.5 dB to 5 dB were briefly studied. The convolutional coding techniques having code rates of 7/8, 2/3, 1/2 are able to provide coding gains in the above range with threshold, sequential, or viterbi decoding. Before the selection of the codec technique takes place, the code rate, coding gain, implementation complexity, cost and the residual error pattern etc. will be studied in detail (in Phase 2).

3.6 Modem

The selection of a suitable modulation and demodulation technique depends on required performance, immunity to impairments and implementation simplicity considerations. In general, differentially detected signals perform inferior to their coherent counterparts. Since power is at a premium the modulation technique should be power efficient. Although bandwidth efficiency in this case is not critical, it is advantageous to minimize the bandwidth required for a carrier so that the channel spacing can be narrower and the number of frequency slots per transponder can be large. A larger value for the ratio of the number of available slots to the number of carriers will help place the carrier in such a way that the intermodulation advantage is increased. Coherent QPSK has both power and bandwidth efficiencies in good combination and the technology is well proven. A detailed simulation study will be undertaken to optimize the performance with respect to filtering technique, adjacent channel interference etc. Problems associated AFC, AGC, frequency agility, phase noise and interference will be studied from an implementation point of view in Phase II.

4.0 CONCLUSIONS

4.1 Digital Satellite Technology

As far as Radio Networks are concerned, choosing satellite technology (as opposed to terrestrial) for program distribution is an important first step in the right direction. The second step is the selection of the SCPC mode of operation (as opposed to multiplexed large bandwidth carriers) which has operational convenience, growth flexibility etc. The third, and perhaps the most important step, is the choice of digital or analog. The advantages of digital technology as compared to analog are obvious in regard to program quality, transmission channel immunity and additional new services capability. The argument in favour of FM is that it requires significantly less bandwidth and therefore more carriers could be accommodated (from a bandwidth point of view) in a transponder. In fact, the transponder is power limited for multicarrier operation and the bandwidth advantage is more illusory than real. Our study suggests that an Anik-D type transponder can deliver about 23 FM SCPC carriers (using Wegener's 'Panda' SCPC receiver) using a 4.5m antenna and 120°K LNA receiver. Under similar conditions, a digital SCPC (with an FEC having a coding gain of 2.5 dB) can deliver about 8 carriers. This means 16 mono 15-kHz channels plus 16 32-kbps data channels. However the trend reverses when the FEC coding gain is increased to say 5 dB. In this case the transponder can deliver about 15 digital carriers. This means 30, 15-kHz mono and an equal number of 32 kbps data channels. Therefore the key feature for digital equipment is a powerful FEC and a power efficient modem.

With a 3m antenna and 120°K LNA receiver, the transponder can deliver 7 digital carriers (14 15-kHz mono plus data) with an FEC gain of 5 dB. Whereas there will be only 11 carriers (i.e. 11 15-kHz mono) possible using FM SCPC. With 3m or 4.5m dishes either technology is power limited. However the bandwidth limitation comes into effect when a 9.3m dish is used for the receiver.

In summary, with 3m and 4.5m dishes, digital SCPC (with a powerful FEC) can deliver more program channels than FM SCPC. This is made possible because of increased FEC coding gain. Further, a power advantage of about 3 dB per carrier is available for digital carriers since there are twice as many carriers required for the analog transmission for the same number of program channels. A similar advantage can be (a factor of two) can be seen in the number of receivers for the digital SCPC carriers. This will also reflect in favour of digital SCPC in the equipment cost per program channel.

These advantages coupled with backhaul terrestrial digital link (T1) compatibility (with the inclusion of T1 link mux-demux. See Section 3.4), new service capability, cost effective miniaturization and promising technology trends strongly favour a digital SCPC with power, and to some extent bandwidth, efficient implementation. On these considerations digital SCPC clearly out scores FM SCPC.

4.2 PCM-ICOM

As far as PCM derived source coding techniques are concerned, the instantaneous companding (ICOM) appears to have an edge over the near-instantaneous (NICOM) techniques. The PCM technique employing 14 bit to 11 bit instantaneous A-law companding is a CCITT standard. Codec implementation is simple and straightforward. In NICOM different error correction techniques are suggested for bits of different importance. Thus the error correction implementaion is relatively complicated and the use of highly powerful FEC codes becomes difficult. In ICOM, except for the 1 bit parity protection, the error correction (FEC) is done separately and is independent of the source codec. This enables one to use commercially available FEC codecs to achieve large coding gain. Larger coding gains are important because the transponder is power limited. For the same reason, the higher bit rate compression achieved in NICOM as compared ICOM has less practical significance. While the multiplexed NICOM channels easily interface with the 2.048 Mbs hierarchy, ICOM channels can easily interface with 1.544 Mbps hierarchy. Further digital conversion of the 14 bit to 11 bit A-law compressed data stream to a 15 bit to 11 bit μ-law compressed data stream and the reverse process can be hardware implemented relatively easily. These advantages coupled with a near term North American market potential heavily favour the 14 - 11 - ICOM-PCM technique.

It could also be extremely interesting to explore other techniques such as ADM (DOLBY) and ADPCM (SANSUI). The Dolby system may be particularly interesting because of its increased insensitivity to channel errors which permit it to operate at error rates as high as 10^{-4} or more. This will enable the equipment designer to use it to gain additional power margin, to use it to trade with a low cost FEC, or to use it to enhance transponder utilization. Also an ADM (DOLBY) decoder will be extremely cost effective. A forecast decoder IC cost is about U.S. $6.

4.3 Mux - Demux

The channel multiplexer and demultiplexer will have design features suitable to accommodate different program and data channels. The Tl link mux and demux can be used in conjunction with the channel mux-demux or directly.

4.4 FEC Codec

As high coding gain is of primary importance, a powerful FEC technique may be required. However the overall equipment cost will have some constraints on the codec choice.

4.5 Modem

For the above mentioned reasons, the modem should be highly power efficient. Bandwidth efficiency is a welcome feature as this may help reduce adjacent channel and intermodulation interference and also enable the use of high redundancy FECs.

REFERENCES

[1] "Earth Station Specifications and Technical Requirements for Systems Accessing the Telesat Satellites to Provide Partial Channel Services at 6/4 GHz" Telesat Canada, October 1984.

[2] "Study on Digital Modulation and Multiplexing Techniques Appropriate to the Distribution of Radio Programs by Satellite" MCS Final Report File: 8270, DSS: OST81-00256, 3 January, 1983.

APPENDIX A

A.0 INTERFERENCE ANALYSIS

Satellite transponders are typically operated either in single carrier per transponder (SCPT) or in multiple carriers per transponder (MCPT) mode. In either case, each carrier can be used either in single channel per carrier (SCPC) operation or multiplexed channels per carrier (MCPC) operation. The interference to a desired channel can come from a number of sources within and external to the desired satellite link. These interference sources include;

- thermal noise
- adjacent channel
- adjacent transponder
- adjacent satellite
- intermodulation
- terrestrial radio

The channel performance depends on the nature and amount of this interference. Figure A.1 shows a complex system interference model. At the transmit earth station, if multiple carriers are amplified using a nonlinear power amplifier, interference due to intermodulation will occur. This may be denoted by $(C/I)_{IME}$. The desired signal at the transponder input will be corrupted by several sources of interference viz., (1) uplink additive white gaussian noise (AWGN - thermal noise) - $(C/N)_u$, (2) interference from adjacent earth stations transmitting to adjacent transponders - $(C/I)_{ATI}$, and (3) interference from adjacent earth stations transmitting to adjacent satellites - $(C/I)_{AES}$. In the satellite itself, intermodulation interference will occur due to MCPT operation in a nonlinearly driven transponder amplifier - $(C/I)_{IMS}$. The

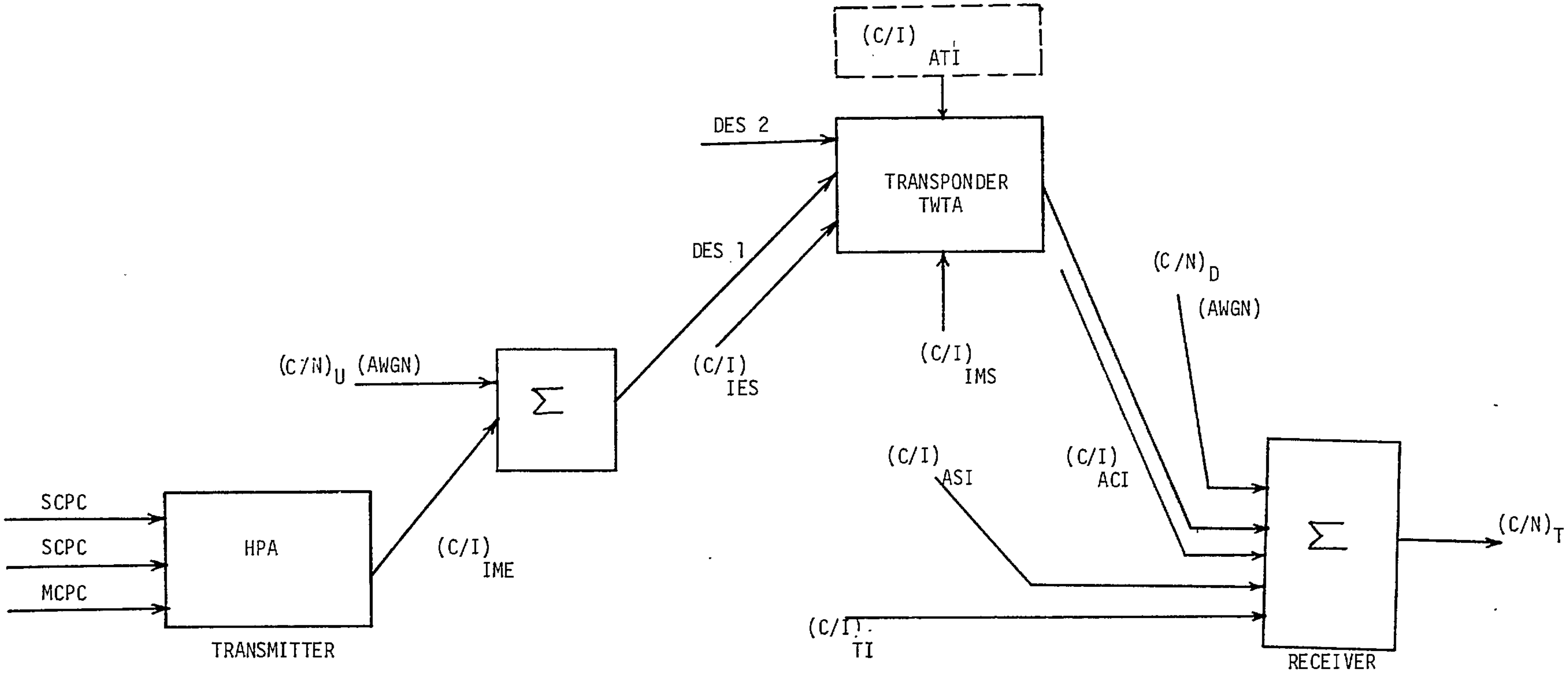

Figure A.1 Overall System Interference Model signal at the earth station receiver input may be corrupted by (1) the downlink AWGN - $(C/N)_D$, (2) the interference from adjacent satellite transmissions - $(C/I)_{ASI}$, and (3) the interference due to terrestrial radio signals $(C/I)_{TI}$. In addition, interference may occur due to adjacent carriers spaced close to the desired signal - $(C/I)_{ACI}$.

It must be pointed out that all the interferers may not be present (or significant) all the time. In other words the interference state is time varying and nonstationary. In general such an interference model is difficult to analyze. A practical approach is to assume a worst case interference state just as we normally assume a worst case level for an interfering signal. In the following, we shall discuss and specify some of the interference levels with respect to the Anik D satellite.

A.1 Adjacent Satellite Interference

The ASI may occur either due to radiation from neighbouring satellites or due to radiation from earth stations pointing towards neighbouring satellites as shown in Figure A.2. The characteristics of ASI may change due to changes in satellite orbital position and replacement activities, and therefore it is difficult to accurately predict ASI levels.

In the case of the Anik D satellite, the present neighbouring satellites which could cause interference are U.S.A., Mexican and other Anik satellites. The current ASI estimates recommended (by Telesat) for Anik D are:

- Uplink: The uplink interference power density at the satellite input due to adjacent satellite systems is approximately -103 dB relative to the single carrier saturating input power.

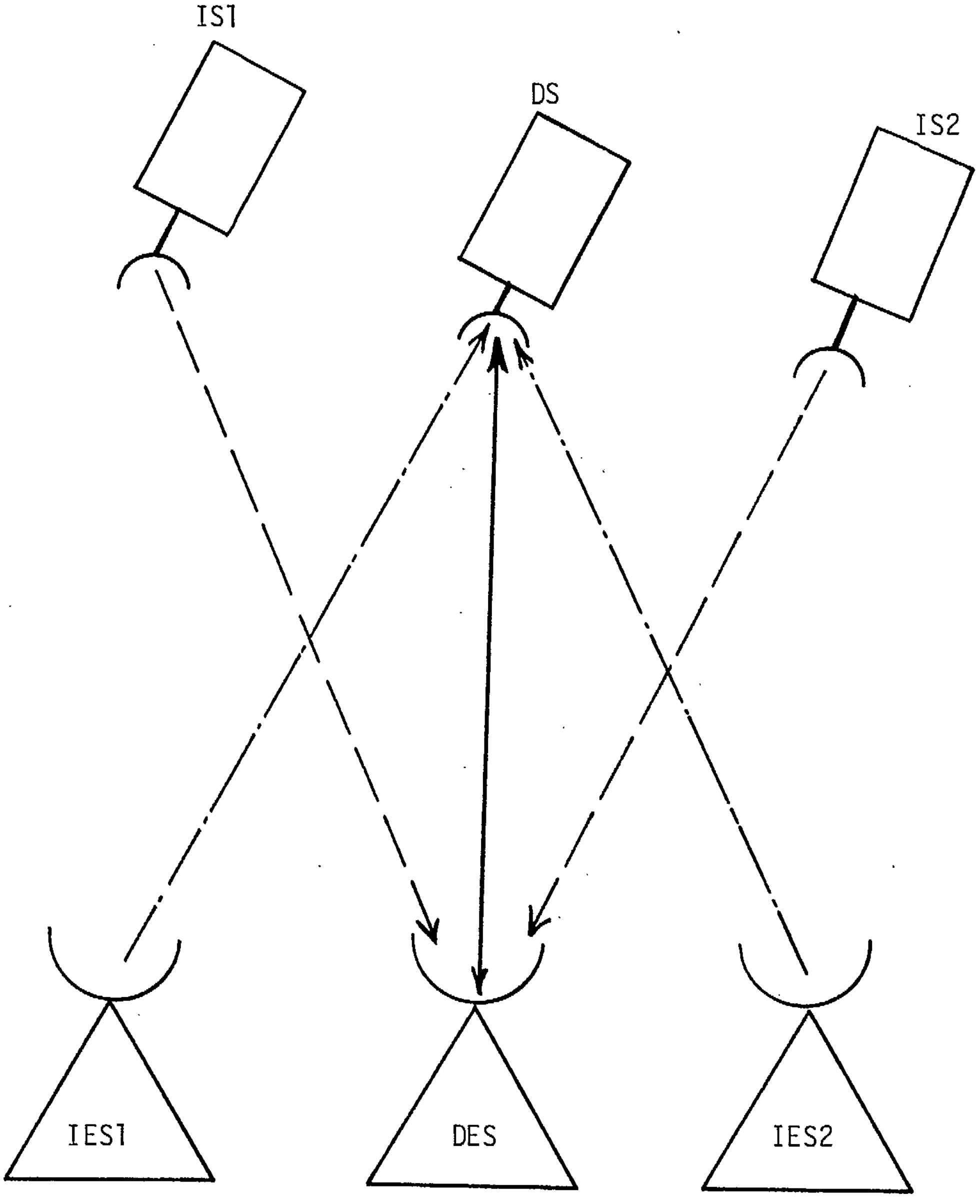

Fig. A.2 Adjacent (two) Satellite Interference Model
I(D)S = Interfering (Desired) Satellite
I(D)ES = Interfering (Desired) Earth Stations

- Downlink: The equivalent downlink EIRP power density at the satellite output depends on the receiving earth station antenna size. Assuming the antenna gain as a function of off-axis angle, θ, is given by $29-25 \log \theta$, the equivalent EIRP power density allocation is approximately $-(13+G_e)$ dBW/Hz where G_e is the receive boresight gain of the earth station antenna.

A.2 Intermodulation Interference

Earth stations accessing an FDMA transponder may often transmit several carriers which will result in multicarrier intermodulation products which interfere with other carriers in the channel. Normally, within the user's allocated bandwidth, there is no specified intermod limit imposed by the transponder leasing agency. However, there are limits to the allowed interference levels outside user's allocated bandwidth.

Telesat specifies that typical operating systems using 7 dB of HPA output backoff would require an allocation for interference power density at the satellite input of about -101 dB relative to the single carrier saturating input power.

For a transponder carrying a homogeneous traffic and operating at 4.5 dB output (TWTA) backoff from the single carrier saturated power, the design value for the intermodulation noise power density shall be -93 dB relative to the single carrier saturated output power of the RF channel. The 3rd order IM levels for two carrier operations in one of the Anik D/B transponders are given in Figure A.3.

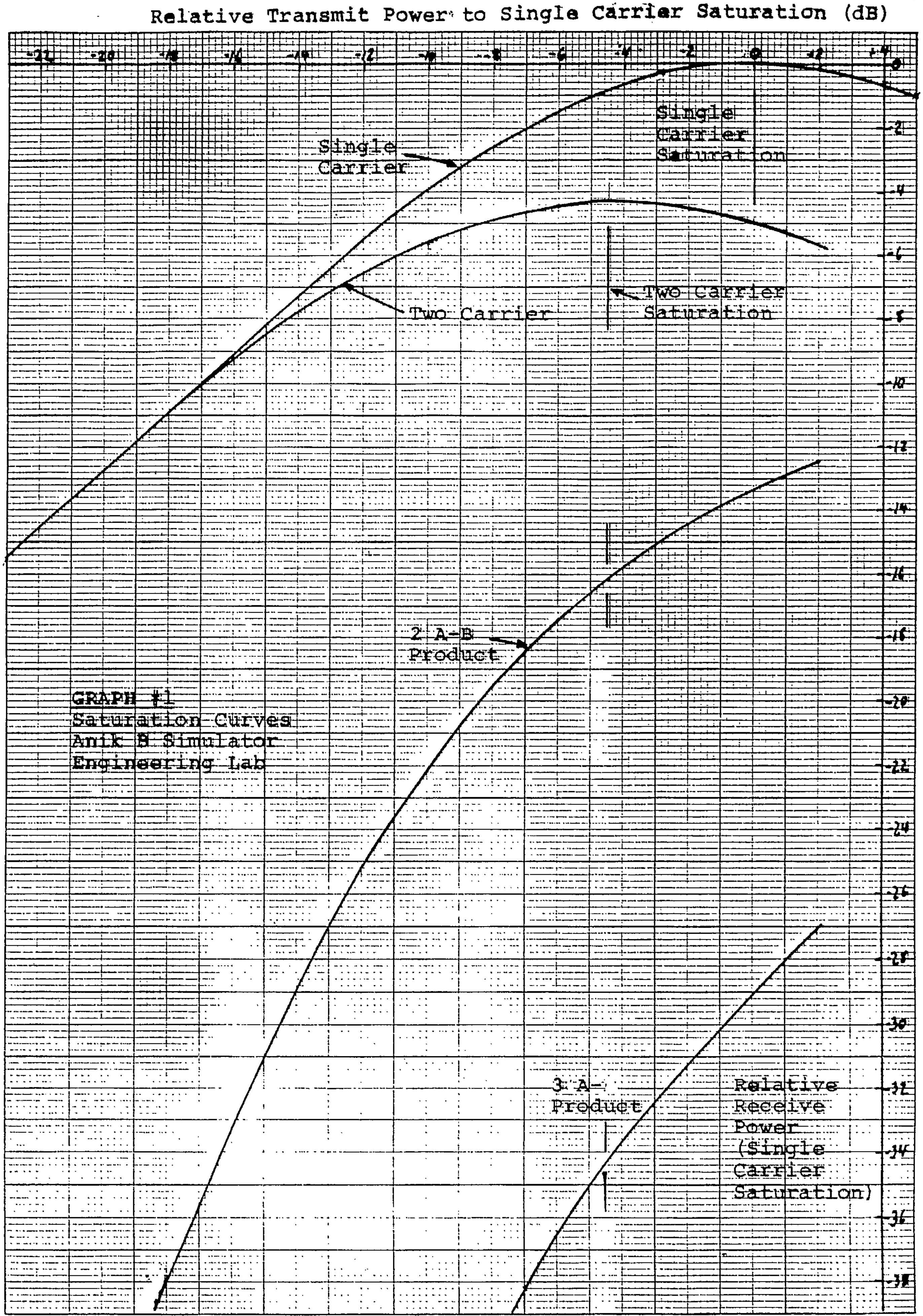
Relative Transmit Power to Single Carrier Saturation (dB)
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
+4
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
Single Carrier
Single Carrier Saturation
Two Carrier
Two Carrier Saturation
2 A-B Product
3 A- Product
Relative Receive Power (Single Carrier Saturation)
GRAPH #1
Saturation Curves
Anik B Simulator
Engineering Lab

Fig. A.3

APPENDIX B

B.0 INTERMODULATION VERSUS TRANSPONDER UTILIZATION

A transponder can be utilized for single carrier operation or for multicarrier operation. In the multicarrier case, a number of configurations are possible depending on the nature of the carriers, levels and spacing (see Figure B.1).

The factors which influence the choice of a configuration are;

- transponder operation (linear or nonlinear)
- size of the earth station (transmit and receive)
- network requirements (topology, access mode etc.).

The aim is to maximize the utilization of transponder power and bandwidth.

For the radio program distribution application, we have to consider both homogeneous (carriers of same modulation, bit rate etc.) and heterogeneous operation. In the former case the transponder is dedicated to only, say, radio program SCPC carriers. The later case can be visualized when the SCPC carriers share the transponder with other narrowband carriers (see Table B.1) and/or wideband carriers such as TV, FDM-FM etc.

B.1 Homogeneous Operation

In the homogeneous operation, the transponder can be shared by uniformly spaced carriers or nonuniformly spaced carriers. Usually, uniform spacing is adopted in a bandwidth limited situation and nonuniform spacing in a power limited situation.

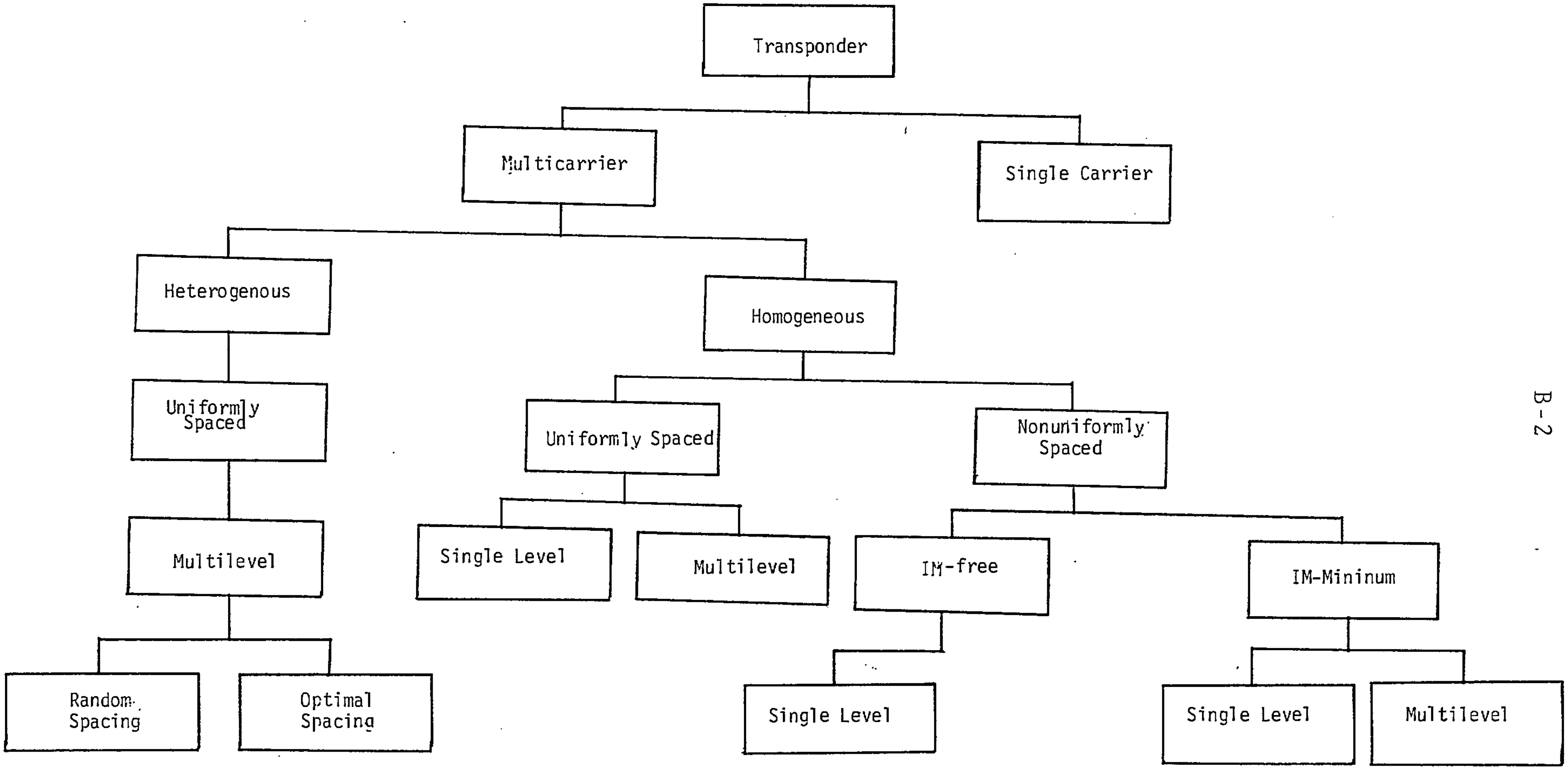

Figure B.1. Transponder Utilization: Different Approaches

CHANNEL TOP BB/ INF. RATE	NBW MHZ	LEVEL dBW	MODULATION	ANTENNA SIZE T/R (METERS
20 KHz	.2	19,16.5	FM	10-15/1.8-4.5
230.4 KBPS	.18	22	QPSK	10/4.5
256 KBPS	.18	22	QPSK	10/4.5
1.544 to 4.5 MBPS	1.0 to 4.0	15 to 22.3	QPSK	5-11/5-11
15 KHz	.18	16.5,19	FM	4.–,15/4.5,3
15 KHz	.12	22	FM	10/1.22
3 KHz	.025	7.5	FM	4.5/4.5
2.5 MBPS	2.5	20	BPSK	11/4.5
8 KHz	.075	8.5	FM	5/5
112 KBPS	.085-.17	4 to 11.5	QPSK	5-15/5-15
32 KBPS	.04	–6,3.5	BPSK	4.5-15/4.5-15
32 KHz	.88	13.3	FM	15/15
131 KBPS	.2	4,14	QPSK	5,15/15,5
122 to 192 KPBS	.11 to .17	4.3 to 7.7	QPSK	11/11
9.6 KBPS	.02	–2.4,–2.7	QPSK	3/5
96 BPS	.005	4.3	QPSK	5/3
257 KPBS	.22	7.8,7.3	QPSK	11/11
4.8 KBPS	.02	8.6	BPSK	5/3
262 KBPS	.27	7.3,7.4	QPSK	11/11
600 KBPS	.5	15	QPSK	11/11
56 KBPS	.036	0,6	QPSK	4.5,10/10,4.5
8 KHz	.026	2	FM	5/5

- analog program channels (15 KHz)
- analog VF channels
- low speed digital signals (4.8-262 kbs)
- medium speed digital signals (1.544-4.5 Mbs)

Table B.1 Possible Carriers in MCPT Operation

B.1.1 Uniform Spacing

In this case the spacing between adjacent carriers is constant although individual carrier levels can vary. Let N_c be the number of carriers and N_s be the number of slots in a transponder, then the bandwidth redundancy (or ratio) for a transponder is defined as

$$r = \frac{N_s}{N_c}$$

and,

$$N_s = \frac{B}{\Delta B}$$

where B is the usable transponder bandwidth, and ΔB the (fundamental) channel spacing.

When $r=1$, the only way that the IM level for single level carriers can be reduced is by increasing the backoff (i.e. operating in or near the linear region). However, the IM levels in certain slots can be reduced by allocating different levels to the carriers. For the radio program application, the question of multilevel carriers will depend on the network configuration, figure of merit of the earth stations and growth flexibility requirements. For an equal level allocation it is expected that the IM will have a maximum level at the center of the transponder.

When $r>1$ the achievable IM reduction increases with r at the cost of poor bandwidth utilization. In this case the channel spacing is $(r.\Delta B)$. The IM levels can be reduced either by backoff or multilevel operation or both. A typical example of uniformly spaced single level carrier allocation and the resulting IM is shown in Figure B.2 [B1].

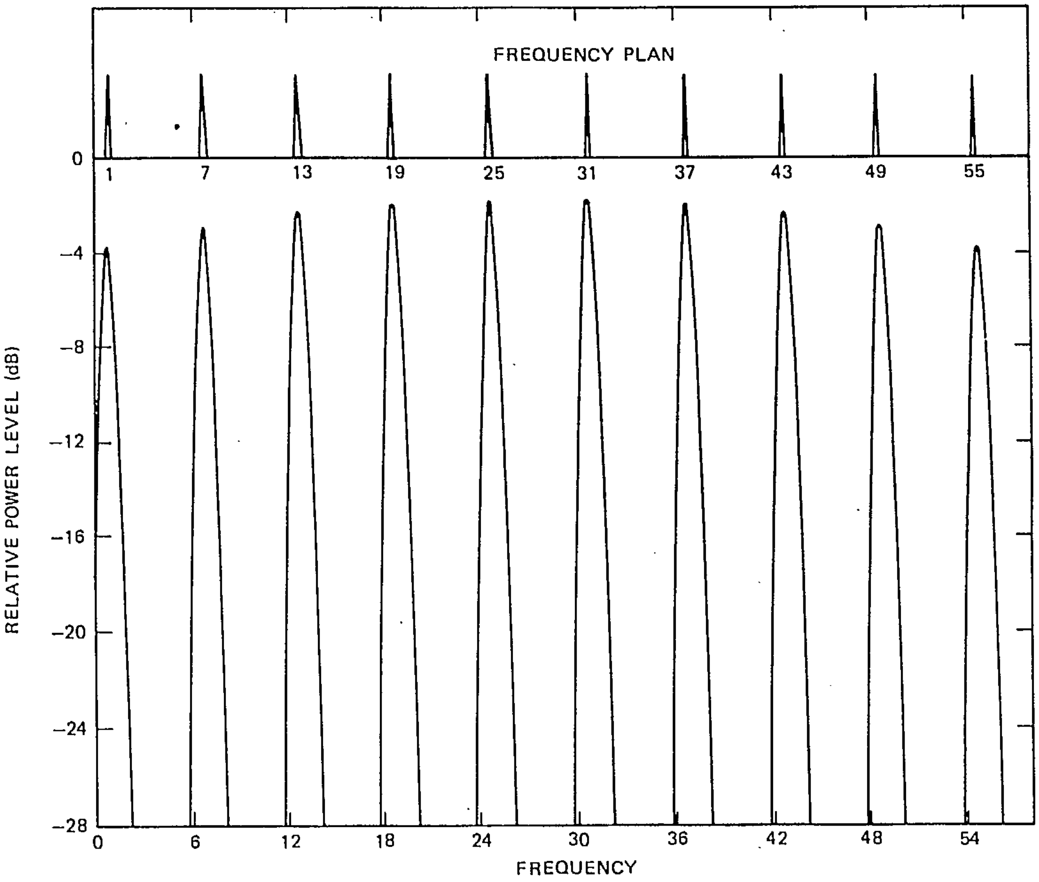

Figure B.2*Third-order Intermodulation Spectrum of a Uniformly Spaced 10-Carrier Plan*

B.1.2 Nonuniform Spacing

In the case of nonuniform spacing it is always true that $r>1$. The IM level can be either minimized or totally eliminated (if enough bandwidth available) in the slot of the desired signal. Here also single-or multilevel assignments can be used. The carrier allocation can be performed in several ways viz.,

- 'brute force' examination
- random assignment
- difference triangle
- successive movement
- successive delete and add

In the 'brute force' method, for a given N_c and N_s, all the possible channel allocation combinations are examined to choose the one which maximizes the carrier to IM interference ratio. This is time consuming even for moderate values of N_c and N_s and may be impractical for multilevel carrier assignments. In the case of the random assignment method, a few random allocation patterns are examined (probably heuristically) to choose the one which maximizes the C/I. The difference triangle is based on a search procedure used in the selection of convolutional self-orthogonal codes. This approach can eliminate IM in the carrier slot but will require high r. In the successive movement method an initial allocation is chosen and one of the carriers is then moved to minimize the IM level. The resultant channel allocation is kept as the initial channel allocation for the next examination. The procedure is repeated until the IM is reduced to desired level. The computation operations involved in this approach are several orders of magnitude less time consuming than the 'brute force' method. In the successive add and delete approach, an initial channel allocation is assumed. A carrier is deleted so as to bring the largest reduction of IM noise in the worst carrier of the resultant channel allocation. An additional carrier can be inserted into an unused frequency slot in the current channel allocation so as to bring the least increase of IM noise in the worst carrier of the resultant channel allocation.

Single Level Carriers

The IM spectrum of N_c=10 single level carriers randomly spaced within N_s=60 slots is given in Figure B.3 [B1]. For the same case, an optimum arrangement where no IM falls on the assigned carrier frequencies is obtained using the difference triangle approach (see Figure B.4 [B1]). The difference triangle approach can also be applied to a constrained frequency plan in which an IM-free allocation is obtained satisfying certain constraints (such as certain channels should be occupied, certain channels should not be occupied etc.).

Figure B.5 shows the IM advantage as a function of bandwidth ratio obtained using the successive delete and add method [B2]. The IM-advantage is defined as the inverse ratio of the amount of IM noise falling into the worst carrier in the derived channel allocation to that in the equally-spaced channel allocation with the same number of carriers. The IM-advantage directly denotes the carrier to intermodulation noise improvement. Figure B.5 also shows the theoreticaly derived upper bound of the IM-advantage. The difference between the simulated IM-advantage and its theoretical limit is shown to decrease with the increase of the number of carriers N_c. The IM-advantage equivalent to the bandwidth ratio is also

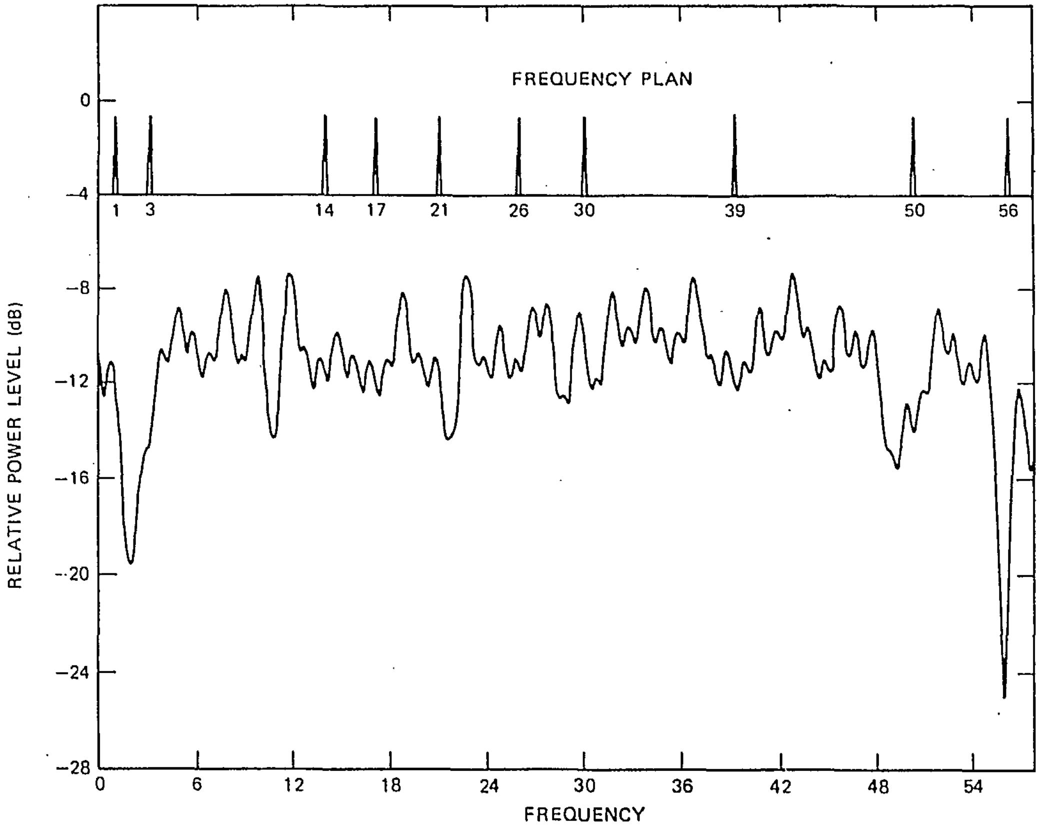

Figure B.3*Third-order Intermodulation Spectrum of a Randomly Spaced 10-Carrier Plan*

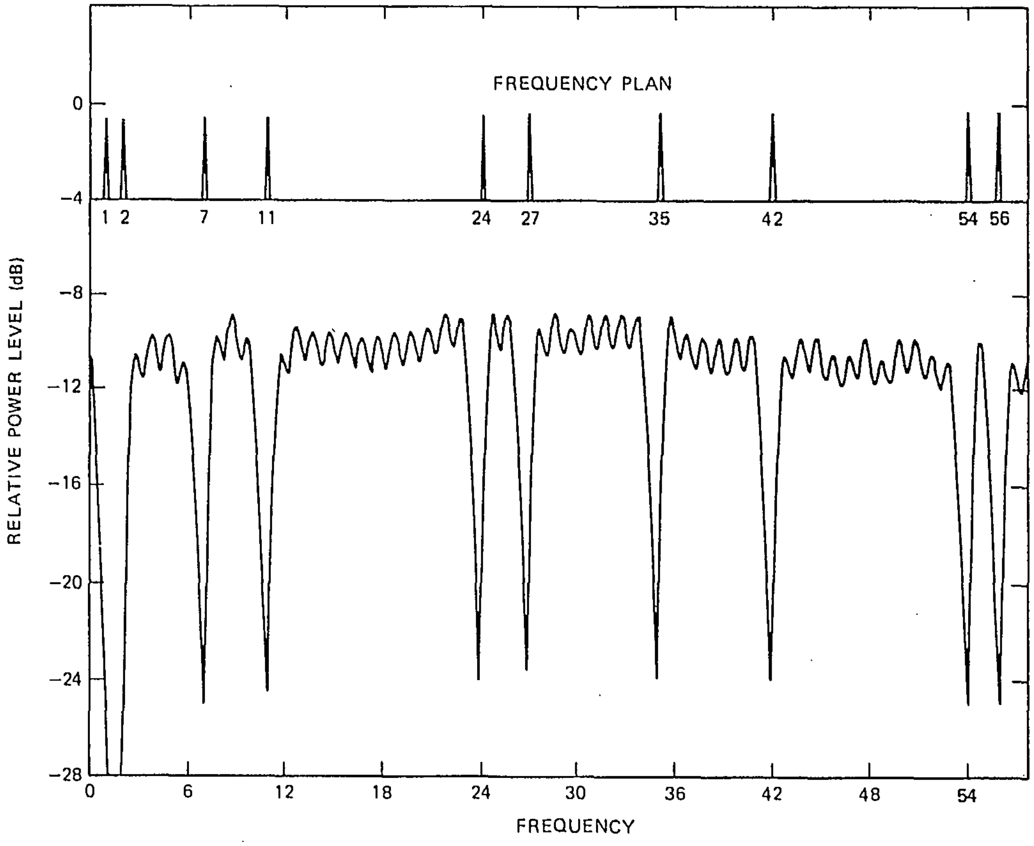

Figure B.4 *Third-order Intermodulation Spectrum of an Optimally Spaced 10-Carrier Plan*

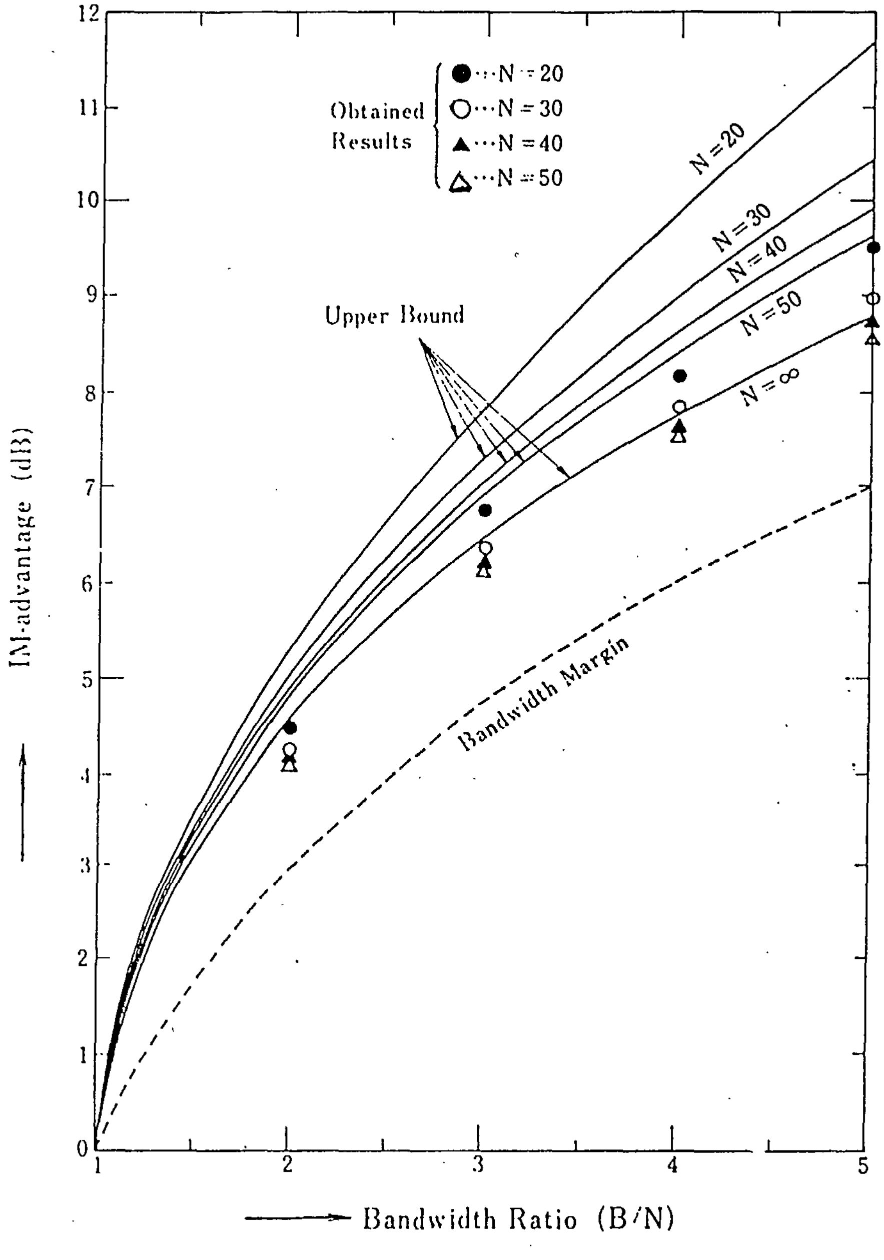

Figure B.5 IM-advantage versus Bandwidth Ratio for Single-level SCPC Systems indicated by a dotted line. If it is assumed that the amount of IM noise falling into every carrier slot in the case of the equally-spaced channel allocation is uniformly spread to unassigned frequency slots, it is expected that the IM-advantage will approach the bandwidth ratio. Figure B.5 shows that the IM advantage obtained is larger than the bandwidth ratio for all the cases considered.

Table B.2 shows the quasi optimum channel allocation for single-level carriers for $N_c = 20$.

Multilevel Carriers

In the case of multilevel carriers it is important to maximize the lowest carrier to intermodulation power ratio rather than to minimize the largest amount of intermodulation power. The carrier allocation can be efficiently done in two ways viz.

(1) dedicated zone method
(2) interleaving method

In the dedicated zone method, dedicated frequency bands are provided for every group within the available bandwidth and the allocation of the carriers is determined within the frequency band. By proper frequency band assignment, the probability of IM power due to a larger carrier falling into the slots of lower level carriers can be reduced.

In the interleaving method, the carriers of different levels are interleaved in a cyclic fashion such that the IM products caused by three carriers of the same group necessarily fall into the frequency slots of their own group. Therefore the IM products caused by carriers of a

TABLE B.2
Optimum Channel Allocations for Single-level SCPC Systems

(a) NUMBER OF CARRIERS = 20

BANDWIDTH RATIO	AVAILABLE NO. OF SLOTS	IM-ADVANTAGE (dB)	CHANNEL ALLOCATION																			
2	40	4.45	1	2	3	5	6	7	10	16	17	19	24	26	27	32	34	36	37	38	39	40
3	60	6.73	1	2	3	6	9	12	13	19	22	27	32	41	43	47	54	55	56	58	59	60
4	80	8.18	1	2	3	4	8	11	16	28	30	41	45	52	57	61	62	70	73	76	79	80
5	100	9.54	1	2	3	5	10	17	29	31	42	45	48	65	67	80	85	89	90	96	98	100

large-level group do not fall into the frequency slots assigned to be lower-level carriers. However this is not true for the IM products caused by a combination of low-and high-level carriers. In fact because of this reason the IM advantage due to the dedicated zone allocation is larger than that due to the interleaving method.

In summary, for multilevel carriers the dedicated zone method is preferable due to the following reasons:

- the IM-advantage for the dedicated zone method is larger than the interleaving method.
- the transmit earth stations can be designed narrowband to uplink all carriers of one level group and the level group chosen can depend on the earth station size.

B.2 Heterogeneous Operation

In heterogeneous operation a transponder can be accessed by carriers having different modulations, bandwidths, and power levels. Normally the multilevel carriers are nonuniformly spaced. As far as intermodulation is concerned, the constituent carriers can be treated as two different cases viz.,

Case 1: Digital SCPC carriers along with the carriers of comparable bandwidth (see Table B.1)

Case 2: Digital SCPC carriers along with the wideband carriers (FDM-FM, TV, etc.).

Case 1: Medium and Narrowband Carriers

This case is typical of digital SCPC carriers sharing a transponder with other carriers of the type given in Table

B.1. Regarding the optimum channel allocation point of view, this is perhaps the most difficult case to deal with since the level, bandwidth, modulation, and spacing can be different for different carriers.

However, approximate relative assessments can be made for frequency plans having wider band carriers by modifying the difference triangle approach so that wider band carriers are represented by clusters of small contiguously spaced carriers, and in the difference set triangle evaluation, not counting the intermodulation products generated among the components of a cluster.

Case 2: Wideband Carriers

Among the wideband carriers, TV is of particular importance here as SCPC channels can be used near the edge of a TV transponder. The problem of mutual interference between these two carriers has been studied in some detail in [B3].

REFERENCE TO APPENDIX B

[B1] R. J. F. Fang and W. A. Sandrin, "Carrier Frequency Assignment for Nonlinear Repeaters", COMSAT Technical Review, vol. 7, Spring 1977, pp. 227-245.

[B2] H. Okinaka, Y. Yasuda, and Y. Hirata, "Optimum Frequency Assignment for Satellite SCPC Systems", IEEE, ICC, 1982, pp. 2E.3.1-6.

[B3] "Study of Digital Modulation and Multiplexing Techniques Appropriate to the Distribution of Radio Programs by Satellite", MCS Final Report File: 8270, DSS File no: 21ST-36001-3496, January 1983.

APPENDIX C - LINK CALCULATIONS

C.0 Objectives

The objectives of the following calculations are to:

1) Determine the available E_b/N_o assuming receivers using 3M antennas and 120 K LNAs (assuming several different values of EIRP/carrier).

2) Determine the number of carriers a transponder can support (Anik D satellite), assuming a typical E_b/N_o requirement for 1×10^{-7} BER.

3) Determine the E_b/N_o available for various information bit rates.

C.1 General Assumptions

As far as possible, parameters have been taken from Telesat sources. The following general parameters are assumed (for Anik D):

- Transponder RF bandwidth: 36 MHz [C1], [C4], [C5]
- Transponder Saturated EIRP: 36 dBW [C3], [C5] (for most of coverage area)
- Saturating Input Flux Density: -80 dBW/m^2 [C5] (for most of coverage area)
- Satellite G/T: -3 dB/K [C3]
- Uplink Frequency (mid-band): 6.1 GHz
- Downlink Frequency (mid-band): 3.9 GHz

- Antenna Elevation Angle: 20°

- BPSK modulation (all calculations would be the same for QPSK)

- an implementation margin of 2.5 dB is assumed to allow for non-ideal filtering, filter imperfections, synchronization imperfections, etc. Although detailed analysis has not been performed for modem performance it is felt that this is a reasonable margin (typical margins range from 2-3 dB).

- a fade margin of 1.6 dB including .1 dB for Downlink Antenna Pointing Errors (assuming stationkeeping given in [C5]), .2 dB for Uplink Transmit Power Variations (from [C7], ±.15 dB was used for HPA having automatic level control) and 1.3 dB for fading due to rain (see Section C.5).

C.2 Downlink Noise Budget - Clear Weather

The following budget is computed taking into account downlink noise.

The downlink C/N_o is given by:

$$[C/N_o]_{down} = EIRP_{sat} - B_o - K + [G/T]_e - L_{pd} \quad (C.1)$$

i.e., $$[C/N_o]_{down} = 68.1 - B_o + [G/T]_e \quad (C.2)$$

Additional losses can be taken into account. The following values are assumed:

Atmospheric Absorbtion	:	0.1 dB
Antenna Pointing Loss	:	included in fade margin
Antenna Polarization Loss	:	0.1 dB
Feed and combiner loss (L_F)	:	0.1 dB

The earth station G/T is dependent on the antenna size and the receiver noise temperature:

$$[G/T]_e = G_e - T_s \text{ (dB/K)} \tag{C.3}$$

where $G_e = (\frac{2\pi r}{\lambda})^2 \eta$

for a 3 m antenna ($\eta = .55$), $G_e = 39.2$ dBi at 3.9 GHz

$$T_s = T_a/L_F + T_o(\frac{L_F - 1}{L_F}) + T_{LNA} \tag{C.4}$$

for a 120 K receiver, 0.1 dB feed loss and an antenna noise temperature of 30 K (reasonable for 20° elevation angle, Scientific Atlanta quotes 27 K for 3 m antenna) the system noise temperature is 156 K (21.9 dBK). This results in a G/T of 17.3 dB/K.

Table C.1 gives $[C/N_o]_{down}$ for various earth stations.

C.3 Uplink Noise Budget (Typical) - Clear Weather

The following budget is computed taking into account uplink noise. The uplink budget can be computed as follows:

$$[C/N_o]_{up} = \phi_{sat} - G(1 \text{ m}^2) - B_i + [G/T]_{sat} - K \tag{C.5}$$

i.e., $$[C/N_o]_{up} = 108.4 - B_i \text{ (dB-Hz)} \tag{C.6}$$

For the range of interest (B_i = 10 to 30 dB) $[C/N_o]_{up}$ ranges from 98.4 to 78.4.

		$[C/N_o]_{down}$ for Different Antennas (dB-Hz)		
Output Backoff (dB)	EIRP (per carrier) (dBW)	3 meter (G/T=17.3 dB/K)	4.5 meter (G/T=22 dB/K)	9.3 meter (G/T=30 dB/K)
8	28	77.4	82.1	90.1
10	26	75.4	80.1	88.1
12	24	73.4	78.1	86.1
14	22	71.4	76.1	84.1
16	20	69.4	74.1	82.1
18	18	67.5	72.1	80.1
20	16	65.4	70.1	78.1
22	14	63.4	68.1	76.1
24	12	61.4	66.1	74.1

Table C.1 - Downlink Budget - Clear Weather

C.4 Interference Budget-Shared Transponder (Based on Information From [C1])

The recommended allocation for uplink cross-polarized interference noise power density at the satellite input is approximately -109 dB relative to the single carrier saturating input power. The recommended allocation for downlink cross-polarized interference noise power density at the satellite output is -104 dB relative to the single carrier saturated output power. This implies

$$[C/I_o]_{XPOL(up)} = -B_i + 109 \text{ (dB-Hz)} \qquad (C.7)$$

$$[C/I_o]_{XPOL(down)} = -B_o + 104 \text{ (dB-Hz)} \qquad (C.8)$$

The allocation for adjacent satellite interference power density at the satellite input is approximately -103 dB relative to the single carrier saturating power, i.e.

$$[C/I_o]_{SAT(up)} = -B_i + 103 \text{ (dB-Hz)} \qquad (C.9)$$

Assuming the antenna gain as a function of the off-axis angle, θ, is given by $29-25 \log \theta$, the equivalent adjacent satellite interference power density is given by:

$$[C/I_o]_{SAT(down)} = EIRP - B_o + (13 + G_e) \text{(dB-Hz)} \qquad (C.10)$$

where G_e is the receive boresight gain of the earth station antenna.

For a typical HPA operating in a multicarrier mode (likely scenario for centralized radio program distribution), a typical allocation for uplink intermodulation noise is

$$[C/I_o]_{IM(up)} = -B_i \text{(per carrier)} + 101 \text{ (dB-Hz)} \qquad (C.11)$$

where B_i refers to the satellite input backoff.

Based on a homogeneous RF channel carrying FDMA traffic and operating at 4.5 dB output backoff from the single carrier saturated output value, the design value for carrier to intermodulation noise power density is

$$[C/I_o]_{IM(down)} = -B_o(\text{per carrier}) + 93 \text{ (dB-Hz)} \tag{C.12}$$

Of course the precise value of intermodulation noise is very dependant on the number of carriers, relative levels and frequency allocations. This allocation includes an allowance for adjacent RF channel interference.

See Tables C.2 and C.3 for the C/I_o values for various backoffs.

C.5 Degradation Due to Rain Attenuation

The long-term statistics of the effective attenuation due to rain can be calculated using the CCIR rain model [C8, C9].

The following results assume that the height of the earth stations above mean sea level, h_o, is zero (resulting in a negligible increase in the computed attenuation).

Table C.4 indicates the resulting attenuation for the various climatic regions of Canada at typical latitudes and assuming elevation angles of 20°. As can be seen the attenuations are small (a margin of 0.2 dB is sufficient for 99.99% availability). The increase of noise temperature due to this attenuation is approximately 12 K (i.e. decrease in $[C/N_o]_{down}$ of approximately .3 dB assuming a clear weather receiver noise temperature of 156 K). This implies that a margin of .5 dB is required on $[C/N_o]_{down}$.

Input Backoff (per carrier)	$[C/I_o]_{XPOL}$	$[C/I_o]_{SAT}$	$[C/I_o]_{IM}$*	$[C/I_o]_{up}$
10	99	93	91	88.5
12	97	91	89	86.5
14	95	89	87	84.5
16	93	87	85	82.5
18	91	85	83	80.5
20	89	83	81	78.5
22	87	81	79	76.5
24	85	79	77	74.5
26	83	77	75	72.5
28	81	75	73	70.5
30	79	73	71	68.5

Note: All C/I_o values in dB-Hz

*Assumes typical HPA with 7 dB backoff.

Table C.2 - Uplink Interference

Output Backoff (per carrier)	$[C/I_o]_{XPOL}$	$[C/I_o]_{SAT}$**	$[C/I_o]_{IM}$*	$[C/I_o]_{down}$***
6	98	82.2	87	80.9
8	96	80.2	85	78.9
10	94	78.2	83	76.9
12	92	76.2	81	74.9
14	90	74.2	79	72.9
16	88	72.2	77	70.9
18	86	70.2	75	68.9
20	84	68.2	73	66.9
22	82	66.2	71	64.9
24	80	64.2	69	62.9
26	78	62.2	67	60.9
28	76	60.2	65	58.9

Note: All C/I_o values in dB-Hz.

*Assumes homogeneous RF channel carrying FDMA traffic and operating at 4.5 dB output backoff.
**Assumes EIRP = 36 dBW, G_e = 39.2 dBi (3.0 m, .55 efficiency).
***For the 4.5 m antenna, C/I_o would increase by about 2.3 dB. For the 9.3 m antenna C/I_o would increase by about 4.7 dB.

Table C.3 - Downlink Interference

Climatic Region**	Rain Rate(mm/h)		Latitude	Attenuation (dB) exceeded	
	0.01%	0.1%		0.01%	0.1%
A	8	2	70°N	<0.03 dB	<0.01 dB
B	12	3	50°N	<0.06 dB	<0.02 dB
			60°N	<0.05 dB	<0.02 dB
C	15	5	50°N	<0.06 dB	<0.02 dB
			60°N	<0.05 dB	<0.02 dB
D	19	8	50°N	~0.06 dB	~0.02 dB
			60°N	~0.05 dB	~0.02 dB
E	22	6	50°N	~0.1 dB	~0.04 dB
F	28	8	50°N	~0.13 dB	~0.05 dB
K*	42	12	50°N	~0.25 dB	~0.1 dB

*In actual fact no earth station could have an elevation angle of 20° in climatic region K.

**For climatic regions of Canada see Figure 11 [C9].

Table C.4 - Downlink Signal Attenuation due to Rain

On the uplink path the attenuation at Allan Park (climatic region K*, elevation angle better than 30°) is approximately .85 dB (99.99% availability). No significant increase in satellite receiver system noise temperature results from rain attenuation.

Given the spatial separation of transmit and receive sites, it is unlikely that strong rain fades will occur simultaneously on both links. In order to sum up the effects of rain fades on the overall link, the fades should be summed up on a percentage time basis. An overbound on this would be to assume both fades occur simultaneously.

A fade on the uplink will cause a decrease in the carrier power level at the satellite and at the receiving earth station. It will in fact decrease the intermodulation noise, but this effect will be minimal if the transponder characteristics are approximately linear at the operating point. The net result is that a fade on the uplink results in a dB-for-dB degradation in $[C/N]_{total}$.

A fade on the downlink will cause a decrease in the carrier power level at the receiving earth station. This will decrease $[C/N]_{down}$ but all other ratios will remain the same. As a result, an overbound on the effect of downlink fades will be a dB-for-dB degradation in $[C/N]_{total}$. In fact, for the 3m, 120K receiver, this overbound won't be very large.

As a result of the above discussion a margin of approximately 1.3 dB should be sufficient for 99.99% system availability to allow for fades due to rain. If it could be assumed that fades on the up and downlink were independant then a little more than 1 dB would be sufficient. The pessimistic overbound will be assumed.

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*Worst case since this is the worst climatic region in Canada.

Telesat in fact suggests a total fade margin of 2 dB [C6]. It is not known how this figure was arrived at and what other factors this takes into account.

C.6 Calculation of Available E_b/N_o

The available E_b/N_o can be computed from the available $[C/N_o]_{total}$.

$$E_b/N_o = [C/N_o]_{total} - 10 \log R_b - FM(dB) \qquad (C.13)$$

where R_b = Information bit rate (Hz)

FM = fade margin (dB)

and $$[C/N_o]_{total}^{-1} = [C/N_o]_{up}^{-1} + [C/N_o]_{down}^{-1} + C/I_o^{-1}$$

where C/I_o takes into account degradation due to Intermodulation, Adjacent Channel Interference, etc.

From Sections C.2, C.3 and C.4 it is apparent that the individual carrier-to-noise density ratios are very dependent on the transponder backoffs (input backoffs for uplink ratios and output backoffs for the downlink ratios). In order to combine the two types of ratios the relationship between output backoff and input backoff is very critical. This relationship is very dependent on the number, types and relative powers of the carriers accessing a particular transponder.

In [C1] it is stated that a typical operating point for a multicarrier transponder is a 9 dB total input backoff which results in a 4.5 dB total output backoff. This shall be used as a starting point. The actual relationship for an individual carrier would then be

$$B_i = 9 - 10 \log(p) \text{ dB} \quad (C.14)$$

$$B_o = 4.5 - 10 \log(p) \text{ dB} \quad (C.15)$$

where p is the fraction of the total power allocated to the individual carrier. For carriers of equal power p=1/N, where N is the number of carriers in a transponder.

Using this assumption the available E_b/N_o (energy-per-information bit to noise density ratio) can be computed as a function of power available to the individual carrier (see Table C.5) given an assumed information bit rate of 800 kbps and a fade margin of 1.6 dB.

For the 4.5 meter antenna, $[C/N_o]_{down}$ increases by 4.7 dB and $[C/I_o]_{down}$ increases by 2.3 dB giving a net increase in E_b/N_o of 3.1 dB. For the 9.3 meter antenna, $[C/N_o]_{down}$ increases by 12.7 dB and $[C/I_o]_{down}$ increases by 4.7 dB giving a net increase in E_b/N_o of 6.2 dB (note: the budget for this earth station is dominated by interference noise power).

See Figures C.1 and C.2 for plots of available C/N_o and E_b/N_o versus EIRP/ channel for the three receive stations.

C.7 Total Transponder Budget

The typical E_b/N_o requirement can be approximately given by

$$[E_b/N_o]_{required} = [E_b/N_o]_{ideal} + M_i - G_{coding} \quad (C.16)$$

where M_i = implementation margin (uncoded)

G_{coding} = theoretical coding gain in E_b/N_o over ideal modem performance (assuming unlimited bandwidth)

Fraction of Total Power	B_i	B_o	EIRP (per carrier)	$[C/N_o]_{down}^*$	$[C/N_o]_{up}$	$[C/I_o]_{up}$	$[C/I_o]_{down}^*$	C/N_o	E_b/N_o
.2	16.0	11.5	24.5	73.9	92.4	82.5	75.4	71.2	10.6
.15	17.2	12.7	23.3	72.7	91.2	81.3	74.2	70.0	9.4
.14	17.5	13.0	23	72.4	90.9	81.0	73.9	69.7	9.1
.13	17.9	13.4	22.6	72.0	90.5	80.6	73.5	69.3	8.7
.12	18.2	13.7	22.3	76.7	90.2	80.3	73.2	69.0	8.4
.11	18.6	14.1	21.9	76.3	89.8	79.9	72.8	68.6	8.0
.10	19	14.5	21.5	70.9	89.4	79.5	72.4	68.2	7.6
.09	19.5	15	21	70.4	88.9	79	71.9	67.7	7.1
.08	20	15.5	20.5	69.9	88.4	78.5	71.4	67.2	6.6
.07	20.5	16	20	69.4	87.9	78.0	70.9	66.7	6.1
.06	21.2	16.7	19.3	69.7	87.2	77.3	70.7	66.0	5.4

*Assumes receive station consisting of 3 meter antenna with 120 K LNA.

Table C.5 - Available E_b/N_o

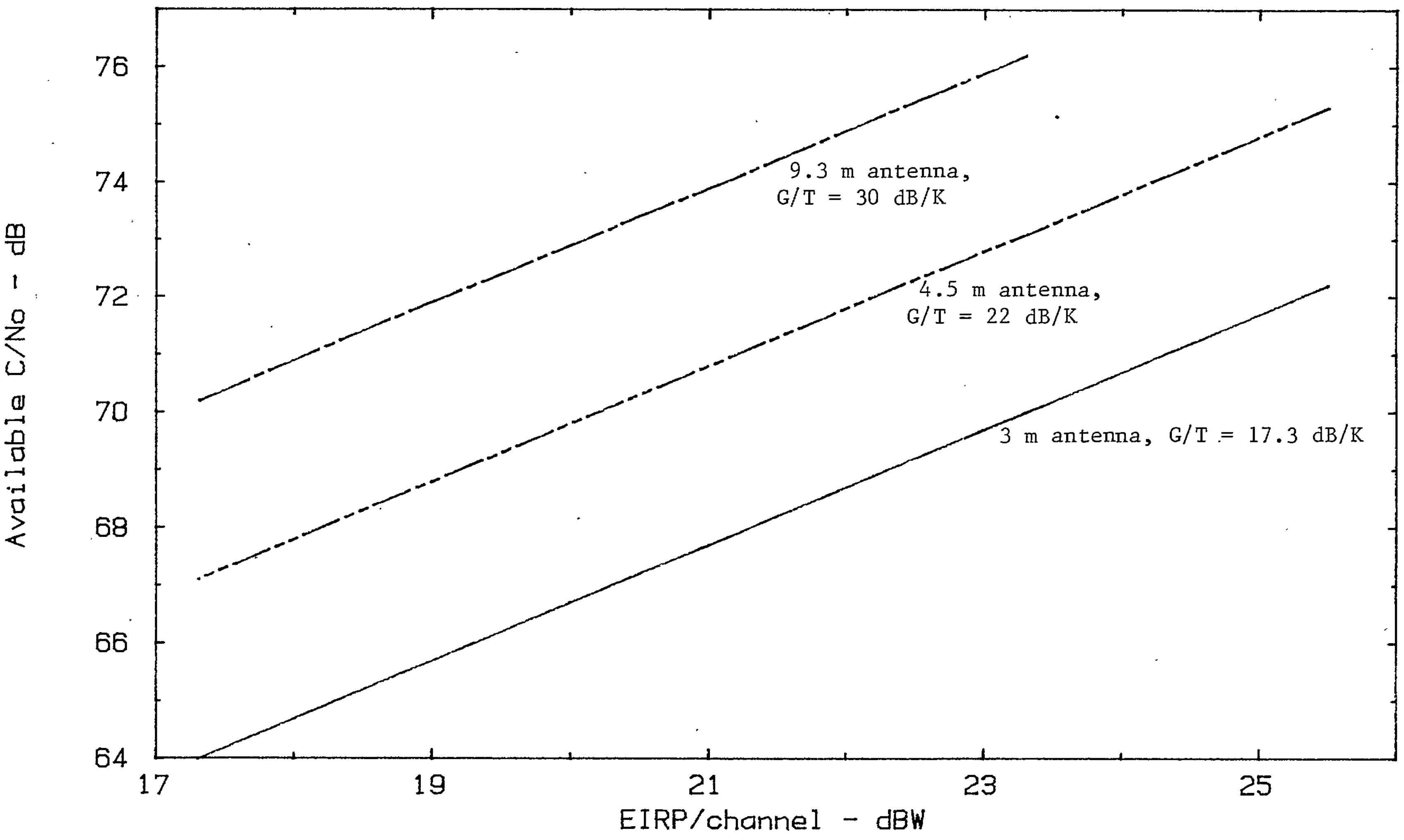

Figure C.1 Available C/N_o for Different Earth Stations

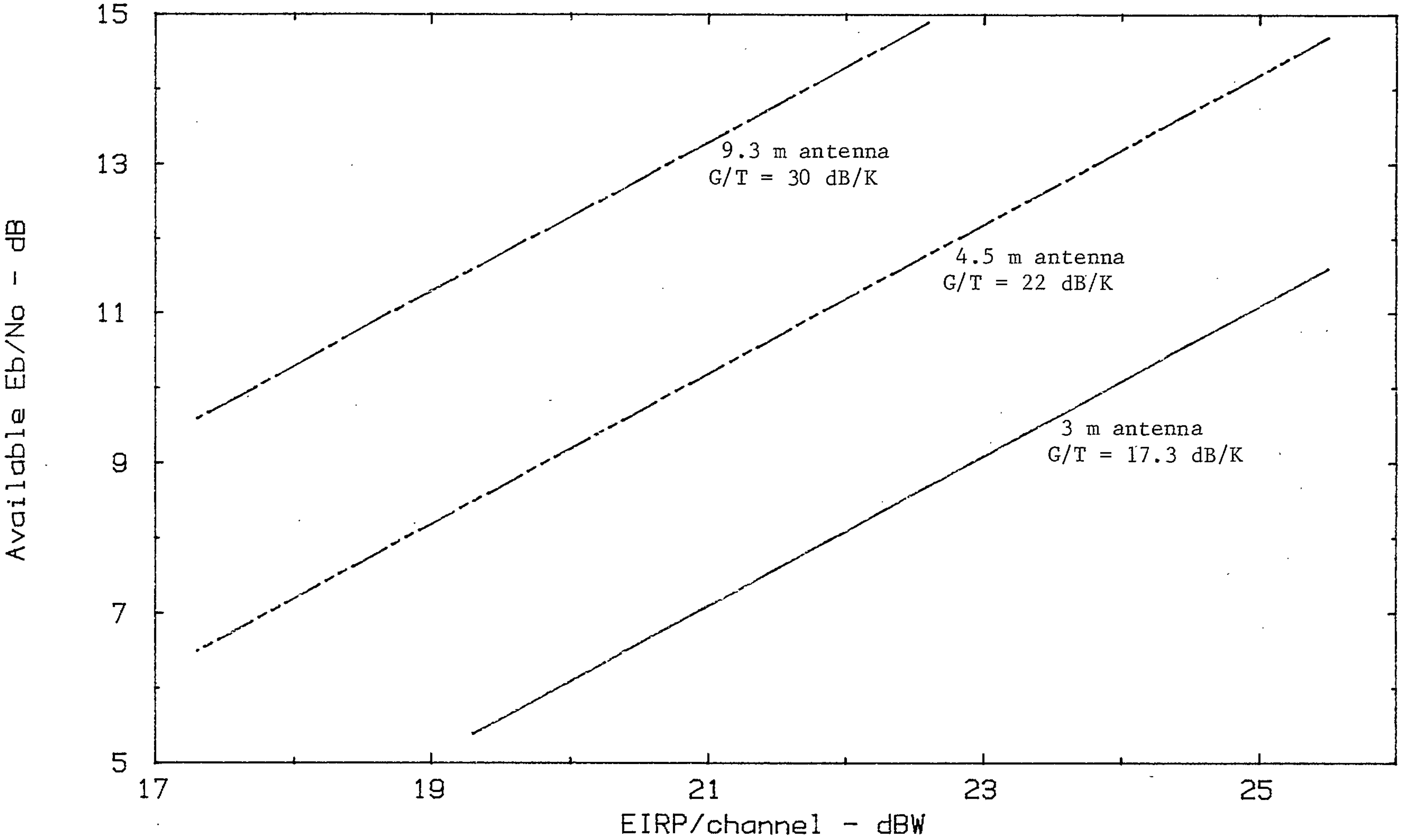

Figure C.2 Available E_b/N_o for Different Earth Station
(Assuming information bit rate of 800 Kbps)

At a 10^{-7} bit error rate, a E_b/N_o of 11.3 dB is required ideally for BPSK or QPSK. From Section C.1, the implementation margin is assumed to be 2.5 dB. Two different coding gains are considered, 5.0 dB and 2.5 dB. Therefore the two different values of $[E_b/N_o]$ are 8.8 dB and 11.3 dB, respectively.

Looking at the previous computation (Section C.6) it is apparent that these values can be met using output backoffs of 13.3 dB and 10.8 dB (for the 3m earth station). From the power proportions it is apparent that 7 and 4 carriers are possible. See Table C.6 for a comparison.

It must be noted the above results were derived using the typical operating point (B_i = 9 dB, B_o = 4.5 dB) and intermodulation noise level ($[C/I_o]_{IM} = 93 - B_o$ dB) given in [C1]. Given the relative values of uplink versus downlink noise the relative values of B_i and B_o are not very critical (the effect of uplink noise and interference is small, approx. .4 dB in total for the 3m earth station). The variation of intermodulation noise, on the other hand, can have a more significant effect (the effect of intermodulation alone is approx. .5 dB).

Calculations with a proprietary FDMA analysis program* showed that at a 9 dB total input backoff the intermodulation level with 10 equally spaced carriers is approximately 2.5 dB better (C/I_o better by 2.5 dB) than given by Telesat. This results in approximately .2 dB of improvement in $[C/N_o]_{total}$.

C.8 Calculation of E_b/N_o For Various Bit Rates

Given the relationship between C/N_o and EIRP/channel computed in Section C.6, the available E_b/N_o can be computed for various bit rates by (C.13).

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*The FDMA program calculates 3rd order modulated intermodulation products with levels extrapolated from measured 2A-B product levels versus backoff for two equal carriers.

Antenna	Required E_b/N_o	Required EIRP/ Carrier	No. of Carriers*	Available EIRP/ Carrier	Extra Margin	Power Utilization (per carrier)
3 m	8.8 dB	22.7 dBW	7	23.0 dB	.3 dB	13.2%
	11.3 dB	25.2 dBW	4	25.5 dB	.3 dB	23.4%
4.5 m	8.8 dB	19.6	15	19.7 dB	.1 dB	6.5%
	11.3 dB	22.1	8	22.5 dB	.4 dB	11.5%
9.3 m	8.8 dB	16.5	31**	16.6 dB	.1 dB	3.2%
	11.3 dB	19	17	19.2 dB	.2 dB	5.6%

*Assuming total output backoff of 4.5 dB (i.e. 31.5 dBW total power available).

**Not attainable due to bandwidth limitations if BPSK used (limited to approximately 20 carriers with rate 1/2 coding).

Table C.6 - Capacity Calculation

See Figure C.3 for the E_b/N_o available for different bit rates for the various receivers.

C.9 Discussion

The calculations performed her have shown that:

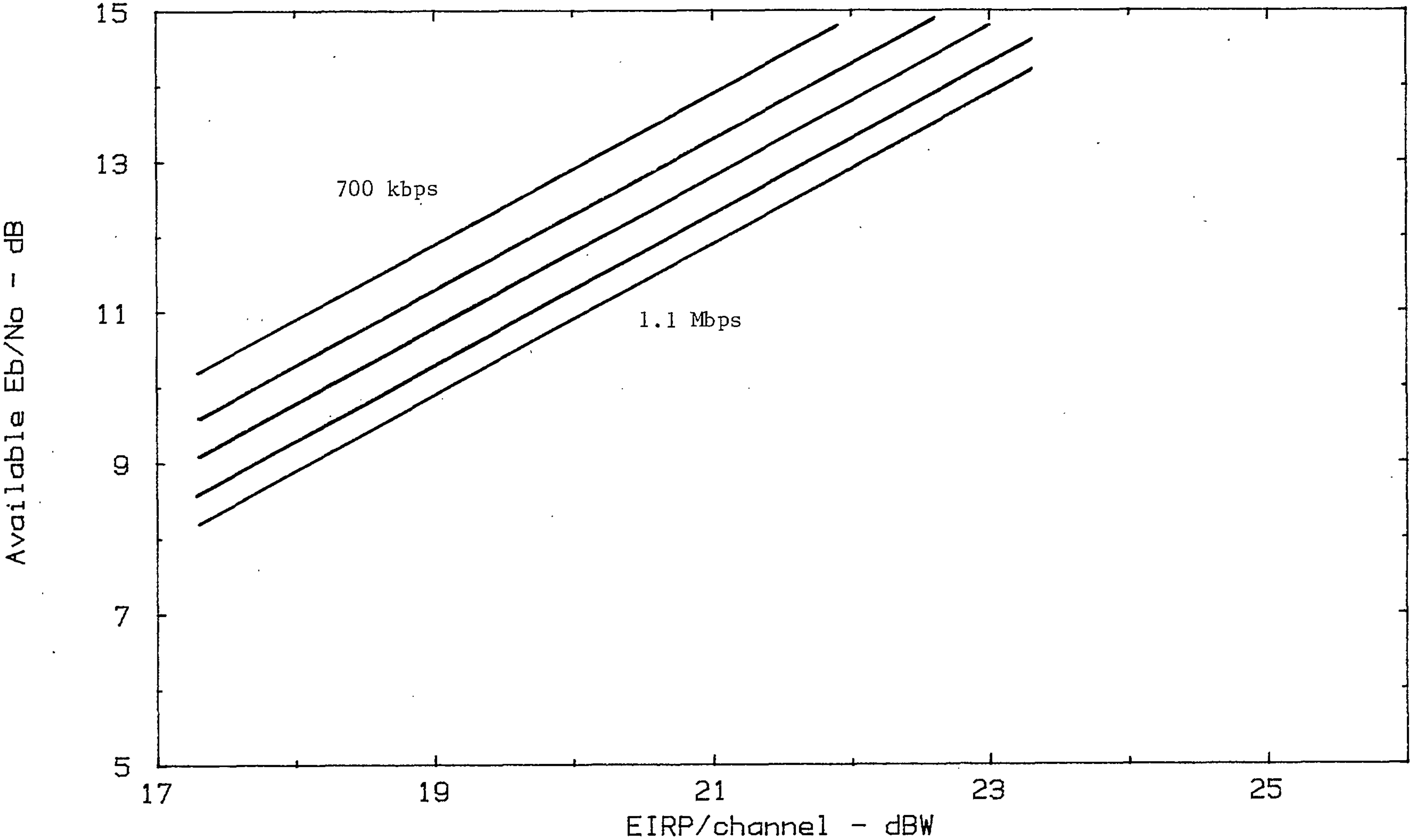
- The performance of the radio program equipment is constrained by power limitations (unless a large receiving antenna is used, e.g. 9.3m antenna).

- Adjacent satellite interference appears to be more dominant than any other interference. In fact it becomes very critical for large antennas (if no tracking system is employed). This conclusion is reached assuming the data given in [C1], i.e. assuming off-axis gain is 29-25 $\log\theta$.

- Uplink noise has little effect unless larger receive antennas are used (in which case $[C/N_o]_{down}$ increases so that it is comparable to $[C/N_o]_{up}$).

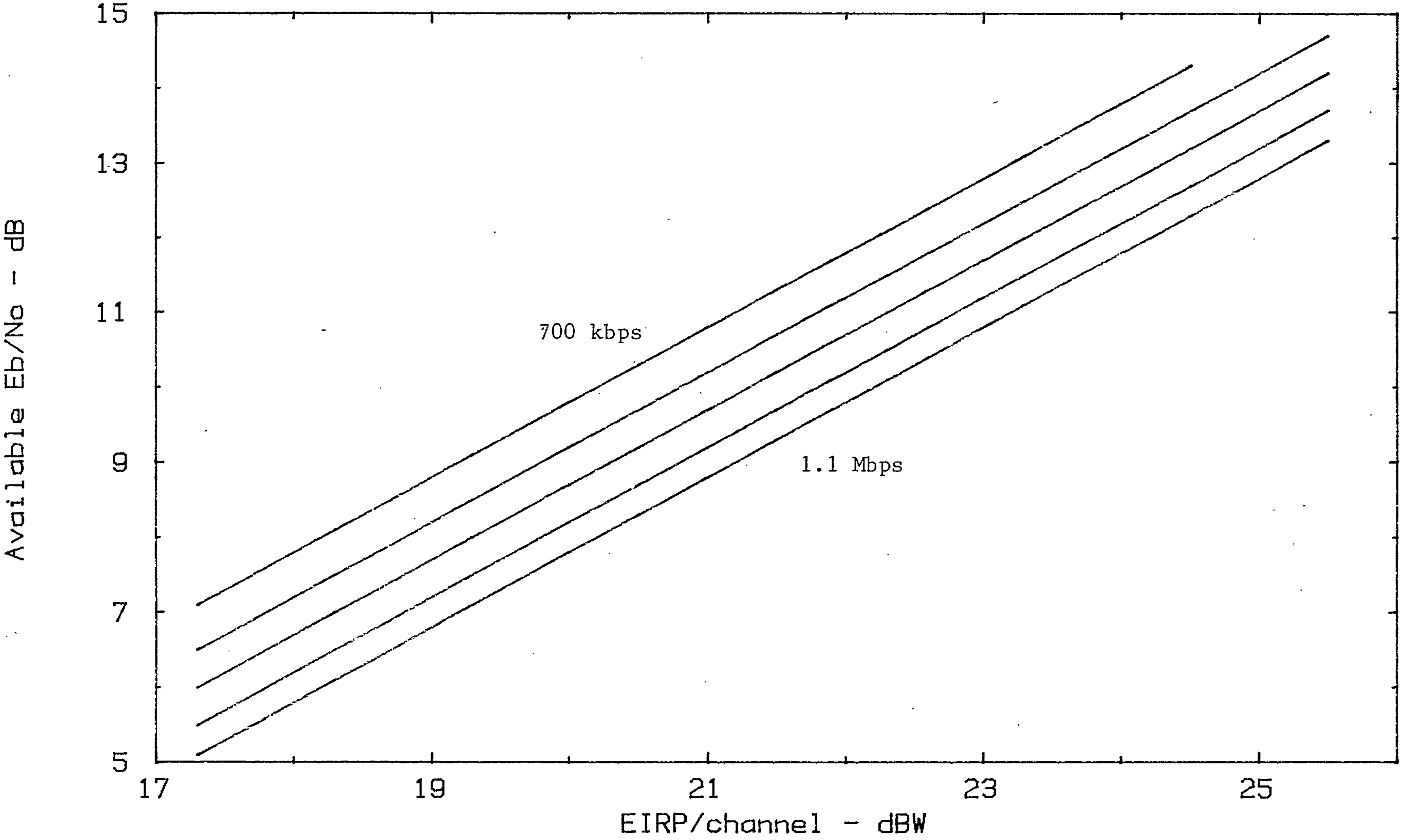
- The performance calculation depends very much on the margins used (1.6 dB fade margin, 2.5 dB implementation margin) and the gain of the coding method used. Changes in any of these values will have a direct dB for dB effect on the amount of satellite power required.

- The approximate improvement in performance over the 3m earth station for the Telesat Earth Stations given in [C4] will be as given in Table C.7.



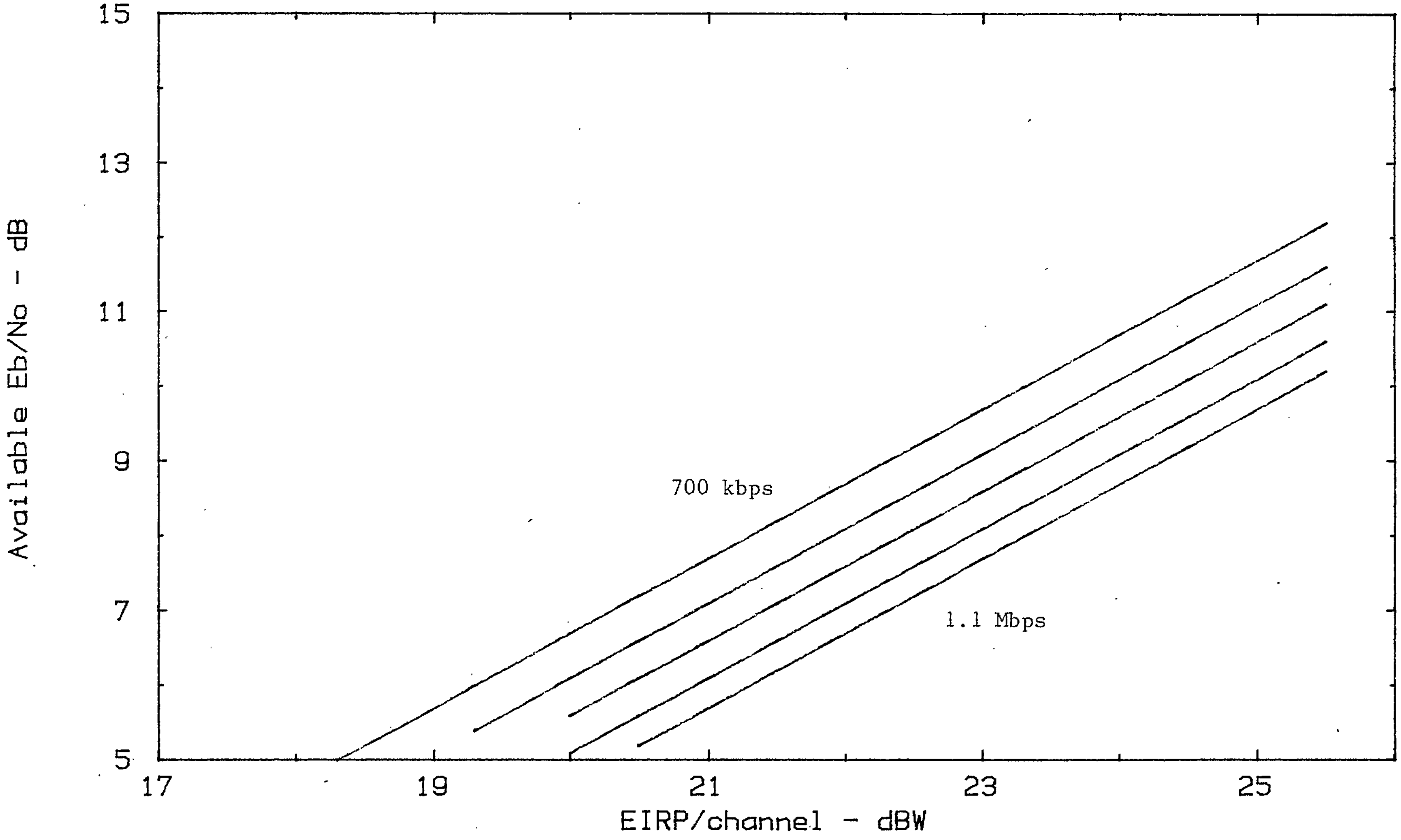
(a) 9.3 m antenna, G/T = 30 dB/K

Figure C.3 Available E_b/N_o for Different Bit Rates



(b) 4.5 m antenna, G/T = 22 dB/K

Figure C.3 Available E_b/N_o for Different Bit Rates



(c) 3 m antenna, G/T - 17.3 dB/K

Figure C.3 Available E_b/N_o for Different Bit Rates

Type	Antenna Diameter	G/T (dB/K)	Improvement over 3 meter (dB)
Remote TV	8	26	4.2 - 5
	8	22	3.1 - 3.7
	4.5	21.5	2.4 - 2.7
Frontier	4.5	18.5	1.4 - 1.7
	3.6	18.5	1.2 - 1.4

Table C.7: Telesat Earth Stations

REFERENCES

[C1] "Earth Station Specifications and Technical Requirements for Systems Accessing the Telesat Satellites to Provide Partial Channel Services at 6/4 GHz", Telesat Canada, October 1984.

[C2] "Customer Owned Earth Stations Satellite Access Requirements Workshop", Telesat Canada, November 1984.

[C3] "Anik D Technical Specification 55-79-1", Telesat Canada, May 15, 1979.

[C4] "A Technical Desciption TC-83-001", Telesat Canada, October 1983.

[C5] "Characteristics of Telesat's 6/4 GHz Satellites (Aniks B and D)", Second Issue, Telesat Canada, October 1, 1984.

[C6] Conversation with D. Gray, Telesat, February 1985.

[C7] "Request for Tender for a 6/4 GHz Communication Satellite Type 'A' Earth Station Section C - Specification B-48/11-5/1, Issue 1", Teleglobe Canada.

[C8] Propagation Data Required for Space Telecommunication Systems, CCIR, Report 564-2, 1982.

[C9] Radiometeorological Data, CCIR, Report 563-2, 1982.