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A FEASIBILITY STUDY OF A 12/14 GHz SCPC SATELLITE COMMUNICATIONS SYSTEM TO MEET TELEPHONY REQUIREMENTS IN RURAL AREAS

MILLER COMMUNICATIONS

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A FEASIBILITY STUDY OF A 12/14 GHz SCPC SATELLITE COMMUNICATIONS SYSTEM TO MEET TELEPHONY REQUIREMENTS IN RURAL AREAS

FINAL REPORT

The work reported herein was performed by Miller Communications Systems Limited for the Department of Communications under Contract Number 1ST77-00131 (Scientific Authority: Dr. R. Bowen).

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ERRATA

Page 1-1, line 4:

....areas of Canada, either on the ANIK-C satellite, or if not feasible, on a different 12/14 GHz satellite which would have technical characteristics indicated in part by this study.

Page 1-1, line 18:

....hubbed system using the ANIK-C satellite, consisting of ....

Page 1-2, 3rd line from bottom

....charge of $500. Then, based on an aggregate amortization annual cost of 20% of the installed capital cost, the annual ....

Page 2-45: should be after 2-60.

Page 5-2, line 11:

....about $100,000. If one then assumes that the annual amortization and interest costs are 20% of the installed capital costs, one could expect a cost per ....

1.0 INTRODUCTION

1.1 Purpose of the Study

The purpose of this study is to investigate the feasibility of using 12/14 GHz SCPC (single channel per carrier) earth stations to provide thin route telephony service to rural areas of Canada on the Anik C satellite.

Specifically, the technical and economic impact of the following are examined:

1) SCPC system performance objectives.

2) SCPC encoding and modulation techniques.

3) Methods of enhancing SCPC transponder utilization:
    - frequency planning
    - voice-activation of carriers
    - demand-assignment
    - up-link power control

4) Frequency stability and control considerations.

5) Hubbed and fully connected network topologies.

6) Adjacent satellite interference.

The report culminates in the conceptual design and preliminary earth station costing for a hubbed system consisting of two classes of stations to serve rural subscribers:

(a) a single-user or Type A earth station providing a single network-quality duplex voice circuit; and

(b) a multi-user or Type B earth station with a 4-circuit capacity.

1.2 Methodology

The cost-effectiveness of a communications system depends on its cost, utilization and performance. These factors must all be considered in assessing the viability of an SCPC satellite system extending or improving telephone service to rural subscribers. This section briefly introduces some economic concepts which underlie the hypothesis and evaluation of a large scale system to operate over Anik C.

Cost per subscriber telephone is the main factor which determines whether a rural SCPC system is economically feasible. The cost per telephone per year of a system possessing a total of N telephones served by $M < N$ demand assigned SCPC satellite channels is given by

$$C = \frac{\text{total earth segment cost}}{N} + \frac{M}{N}\,\text{cost per SCPC satellite channel}$$

$$= \frac{L}{N} \times \text{earth station cost} + \frac{M}{N} \times \frac{\text{total transponder cost}}{\text{total transponder capacity}}$$

where

L = # circuits terminated per earth station.

The ratio $R = \frac{M}{N}$ determines blocking probability for a given subscriber loading (# minutes average use during busy period of day).

For example, suppose a community rural earth station terminating 4 circuits can be installed at a total cost of $80,000 and absorbs a mean annual operating charge of $500. Then, assuming amortization of capital and interest over 5 years, the annual earth segment cost per telephone becomes $4,125. If the total transponder capacity (i.e., permissible number of simultaneous voice-activated carriers) is 1200, R = 10 and the annual transponder lease charge is $3,000,000, then the space segment charge per telephone is only $250. Allowing an additional $125 for installing and maintaining the local loop between the rural household and the community earth station yields a total annual cost per rural line of $4,500.

Widely separated subscribers will be more economically served by single channel terminals on their premises rather than a community station. The break point will occur when the cost of the local loops required to provide access to an optimally located community station* exceeds the saving in RF equipment and maintenance costs.

A $5,000 per telephone per year cost figure is realized in this case if the singlechannel terminal can be installed on subscriber premises at a cost of $23,250 assuming a $100 per year mean operating cost.

Determination of the cost per telephone at which the system becomes economically viable is not addressed in this study. It depends on the cost of alternate means of providing service (best evaluated by telco's) and political decisions as to what percentage of the population should be served (satellite terminal costs are independent of location). The objective here is to engineer a "best" SCPC satellite system for the rural environment, and make available to planners implementation cost information necessary for judicious decision taking.

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* The community station also offers the potential of providing a small local exchange to a number of subscribers exceeding the number of transmit/receive ports and TV reception/low power rebroadcast. Note that our definition of "telephone" implies one dedicated transmit/receive port at an earth terminal.

The report is logically sequenced into five chapters: 1. Introduction, 2. SCPC Techniques and Technology, 3. Rural Network Configurations, 4. Earth Station Requirements and Conceptual Design, 5. Conclusions. Detailed analysis and supporting technical discussions are contained in five Appendices dealing with: A. Adjacent Satellite Interference, B. Fade Margin Requirements, C. Earth Station HPA and Backoff Requirements, D. Cyclic Assignment Multiple Access, E. Generalized SCPC Link Budget Analysis and Optimization.

Chapter 2 examines keys to the effective implementation of SCPC systems, namely: method of interconnection, encoding and modulation, transponder utilization, and frequency control; and considers several novel techniques to reduce both space segment and earth segment costs. Based on the results and recommendations of Chapter 2, Chapter 3 postulates a hubbed SCPC network to serve individual and groups of rural subscribers. Chapter 4 determines earth station requirements, postulates cost-effective earth stations, and costs the system. Chapter 5 is a concise summary of the conclusions from this study.

1.3 Performance Objectives

The quality of telephone service provided can be specified in terms of:

- (i) grade of service
- (ii) circuit noise
- (iii) call set-up time

Grade of service is specified as the percentage of time during a busy period a subscriber is unable to place a call. In our case, this is the sum of the blocking probability (percentage of time all DAMA channels are assigned and there is additional demand for service), probability a call is "lost", and unavailability of the earth station equipment necessary to establish the desired link. A grade of service (over the satellite portion of the system only) of 0.5% can be considered typical of the system envisaged. However, the penalty in satellite utilization (number of channel units/number of SCPC satellite channels) incurred by reducing blocking probability for high capacity systems is small; therefore, the primary economic impact in meeting a high grade of service is the availability requirement it imposes on the rural terminal.

The noise performance of the circuit is normally expressed in picowatts or dBm0 of idle noise in a C-message weighted 300-3400 Hz voice channel bandwidth. Due to the companding action, the subjective performance of FM or Δ-modulated SCPC systems cannot immediately be related to the normal (objective) idle noise specification for circuit quality. Accepted international standards for the "subjectively equivalent" performance of these systems have not been arrived at, although both 32 kbps Δ-modulation and FM operating at threshold (with extension) in a 22.5 kHz bandwidth are gaining acceptance as providing international (40 dBrnCo) circuit quality. This level of circuit performance is consistent with the requirement for "network-quality telephone circuits" as expressed in the Statement of Work, and has been adopted as an objective for purposes of this study.

Call set-up time is the random variable which characterizes the response of the demand assigned multiple access (DAMA) SCPC system in effecting duplex circuits between users. Factors which critically influence mean and 95% call set-up times over the satellite link only are: method of request (random access, polled, or TDMA), request channel duty cycle or frame time, contention probability on request channel, number of handshakes over satellite required to complete call, assignment message lengths, processing time and load at DAMA processor, and hardware (e.g., synthesizer) switching times. The key to minimizing call set-up time with acceptable hardware, software and operational complexity is the selection of DAMA logic and signalling. Considerable attention must therefore be payed to devising and verifying a DAMA system optimized to the operational requirement.

It is noted that quality of service relates exclusively to performance as viewed by the telphone user. The telephone company is also deeply concerned with aspects of performance that relate to system efficiency, and ultimately, cost-effectiveness.

Design alternatives available to meet a given quality of service must be considered and an optimum approach selected. In the case of a demand assigned satellite system this means: (i) minimizing the cost of an SCPC link (including space segment and earth segment components), (ii) maximizing the utilization of this link.

2.0 SCPC TECHNIQUES AND TECHNOLOGY

This section examines methods of deploying SCPC technology and introduces some new concepts which might be usefully applied in a rural satellite system.

2.1 Access Techniques and Non-Homogeneous Systems

There are two access techniques most commonly employed in SCPC systems. These are 'fixed' assignment access and demand assignment access (DAMA). In either case, the presence of earth stations of different size may also give rise to non-homogeneous (different carrier levels to different size stations) systems. A non-homogeneous, demand assigned system implies the need to vary carrier level with destination, further complicating the role of the DAMA controller.

Fixed assignment access, as the name implies, employs pre-assigned frequencies for transmitting and receiving RF carriers at each earth station. Thus each voice circuit between any two nodes requires a dedicated pair of frequencies and transmitters and receivers. Although possessing some advantage of simplicity, the poor utilization of bandwidth and inherent inflexibility of a pre-assigned SCPC system make it an unsuitable method of serving subscribers directly.

With demand assignment, terminals are not assigned fixed frequency RF channels in the transponder but rather any one or one of several of the available transmit/receive pairs of RF channels can be assigned to any two earth stations on demand. Thus the pool of RF channels is available on request, and, depending on demand and grade of service, can serve a much larger number of subscribers.

There are basically two demand assigned SCPC topologies which should be considered for rural applications:

1) direct links between rural terminals permitted (i.e., fully connected system)

2) circuits between rural terminals must be double hopped through a central station

The second scheme clearly has the disadvantage of double hop delay and reduced transponder utilization*, but minimizes up-link EIRP requirements from the rural station and will simplify call routings.

In addition, the first scheme requires that transmit power from the rural station be reduced for calls to the central station, otherwise it could actually be <u>less</u> efficient of satellite power than the second. A fully interconnected system would in fact only receive serious consideration if it were demonstrated that a high proportion of the traffic were between rural subscribers served by satellite.

Since two types of rural earth stations of different capacity are hypothesized in this study, it may be desirable to consider a three level SCPC system. Transponder capacity calculations for such a system becomes more difficult than for a one or two level system, although a general method implemented on a computer is available and is described in Appendix E.

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*Although the bandwidth requirement to support a rural-to-rural link is doubled, the power requirement is only increased by say 25%, depending on differences in G/T between the rural and central stations [1].

2.2 Encoding and Modulation

Pre-emphasized companded FM and 32 kbps variable slope delta-modulation with coherent phase shift keying[†] are the prime contenders in meeting a circuit noise objective of 40 dBrnCo. 64 kbps PCM will provide toll quality (37.5 dBrnCo), but incurs a 6 dB* penalty in power compared to delta, and is not considered in this study. Previous comparison of FM and delta [1] has shown that the difference in fairweather C/N_o required to provide the desired noise performance is small, slightly favouring FM, and this is revealed in Figure 2-1. It is also observed that FM possesses a less graceful threshold characteristic, and therefore might require a greater fade margin. In summary, delta 4-phase CPSK and companded FM are essentially equivalent in terms of satellite power and bandwidth required. Study has also revealed that they are comparable in cost and reliability. The comparison of Δ/4-phase CPSK and FM is summarized in Table 2.1.

Comparison of FM and Δ/PSK in terms of compatibility with the switched network and planned common carrier transmission facilities, plus ease of implementation of voice activation, demand assignment, and echo control may slightly favour a digital approach, but there is no compelling reason to limit the choice at this point.

[†] Recent evaluation of FFSK [2], which has the same theoretical performance as 4-phase CPSK, indicates it may offer certain implementation advantages, in particular with regard to non-linear HPA operation, adjacent channel interference and sensitivity to RF phase jitter. This modulation technique, invented and currently under development in Canada, should also be given serious consideration.

[*] 3 dB for bit rate doubling, 3 dB for reduction in error rate threshold from 10^{-2} to 10^{-4}.

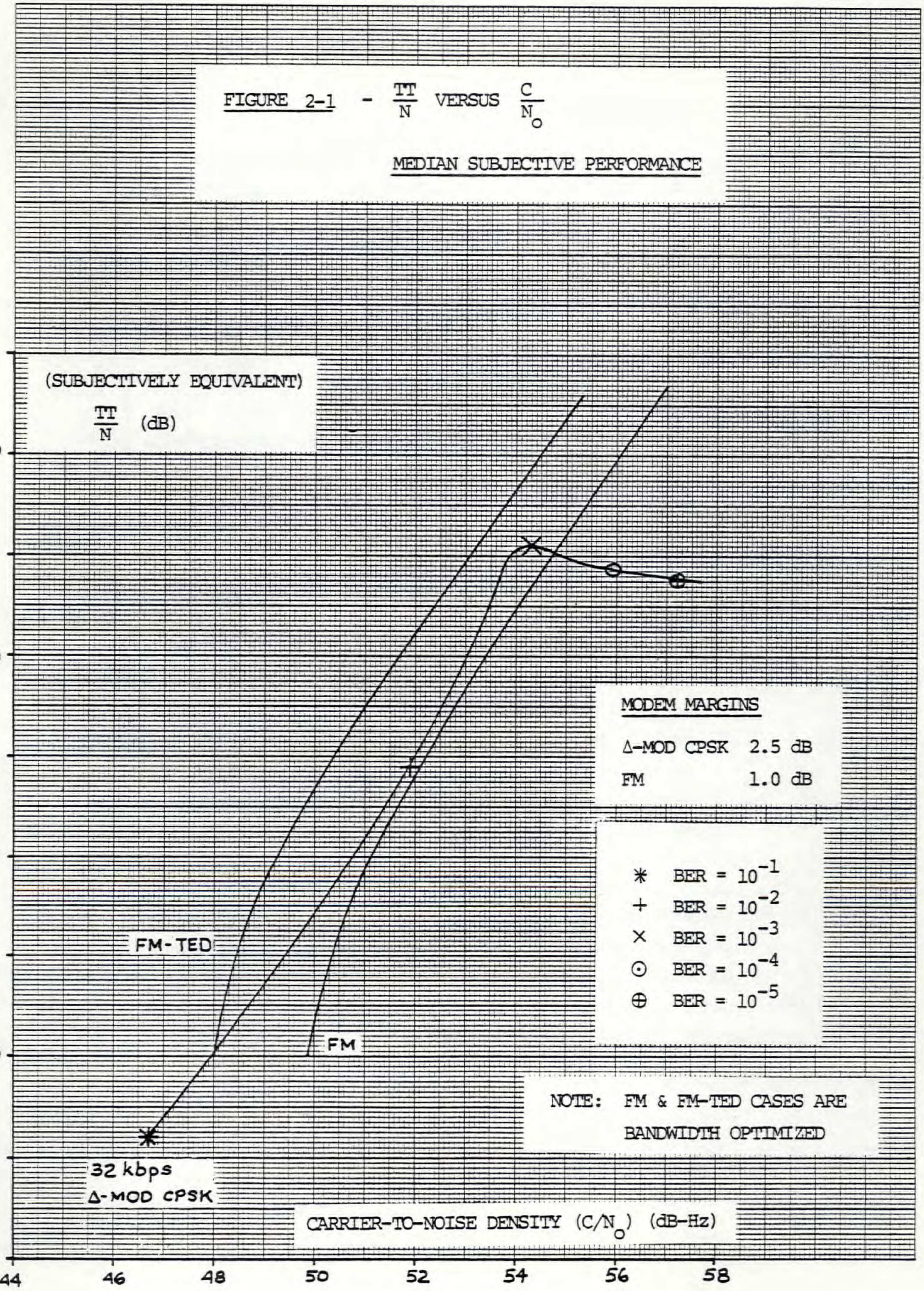


FIGURE 2-1 - $\frac{TT}{N}$ VERSUS $\frac{C}{N_O}$

MEDIAN SUBJECTIVE PERFORMANCE

TABLE 2.1

COMPARISON OF Δ-MOD AND FM SCPC TECHNIQUES

	Variable Slope Δ-Mod/CPSK	Companded Emphasized FM With Threshold Extension Demodulation
Circuit Quality	Determined by encoding rate (quantization) and C/N_o (bit errors). Threshold normally at 10^{-2} BER.	Determined by C/N_o and deviation. Threshold at $C/N_o = 7$ dB.
Transmission Efficiency	C/N_o and RF bandwidth requirements for given circuit quality approximately equal.	
Network Flexibility	Digital format permits efficient digital multiplexing of voice and data and possibly more efficient demand assignment (d.a.) signalling. Circuit quality at a given bit rate is not greatly dependent on earth station G/T - this implies non-optimum utilization of satellite resources if a 2 circuit performance network is required.	FM offers more linear baseband frequency response, and hence can be used to transmit high speed voice band data and radio programs. For an equal carrier DAMA SCPC system, FM provides lower circuit noise into higher G/T gateway terminal(s), thereby efficiently matching space/earth segment resources to a 2 circuit quality requirement.
Sensitivity to C/N_o Variations	Digital system degrades gracefully and provides intelligibility to error rates of 10^{-1}. Circuit quality limited by quantization noise (i.e., C/N_o independent) for BER's less than 10^{-3}.	Performance degrades very quickly below threshold. Above threshold S/N improves with C/N_o on a dB for dB basis.
Sensitivity to Transmission Distortion & Interference	A PSK carrier possesses amplitude fluctuations and is therefore sensitive to limiting and AM/PM conversion in earth station HPA. The associated backoff penalty with single carrier operation increases earth station TWT size by 2-3 dB. A CPSK carrier is somewhat insensitive to co-channel interference.	Constant amplitude nature of FM means HPA can be operated at saturation for a single carrier input. For multicarrier operation required backoff is determined by both intermodulation and intelligible crosstalk requirements. Interleaving can be used to reduce effects of narrow-band interference from adjacent satellite SCPC systems.
Channel Unit Cost & Reliability	Comparable in moderate quantities. Large Scale Integration could significantly reduce unit cost of digital channel unit for sufficiently large market.	

The underlying assumption in this study has been that network quality performance shall be provided at both ends of the rural satellite circuit. Relaxing this objective permits a reduction in required C/N_o (see Figure 2-1) and a lowering of the cost per telephone. A split circuit quality (37.5 dBrnCo into switched network, 44 dBrnCo to rural subscriber) system of the type currently serving Frobisher Bay and Resolute Bay is particularly well matched to the anticipated parameters of the rural and gateway stations. Instead of having two carrier levels to equalize received C/N_o's at these stations, a single carrier level is employed and noise performance <u>to</u> the rural subscriber relaxed. Such an arrangement improves transponder utilization and avoids power control and up-link interference problems in the fully connected Type 1 system. The continued improvement in noise performance with increasing C/N_o well past threshold gives FM the advantage of rural↔rural or rural↔gateway transmission compatibility (i.e., no change in transmission parameters required) and excellent noise performance at the rural terminal under <u>unfaded</u> conditions. The two circuit quality concept also applies to occasional rural-to-rural calling or special pre-assigned circuits in the Type 2 (hubbed) configuration.

2.3 <u>Methods of Enhancing Transponder Utilization</u>

2.3.1 Frequency Planning

The selection of carrier frequencies in either a pre-assigned or demand assigned system may be of considerable importance in optimizing space segment utilization or reducing earth terminal cost. There is considerable freedom in assigning transmit frequencies to the participating stations because: (i) in a power limited system the number of simultaneous satellite links which can be supported falls well beclow the bandwidth capacity of the system, (ii) a set of "usable" SCPC frequencies can be assigned to individual stations in a variety of ways. The following aspects should be considered in allocating frequencies to a given multi-channel earth station:

IM product filtering
output combining
transmit/receive frequency synthesis

and within the satellite transponder:

IM product noise contribution
adjacent satellite interference
adjacent (SCPC) channel interference

These factors are considered briefly and an overall rationale for assigning frequencies described.

For a single channel (Type A) earth station one transmitter is operated in the single carrier mode - IM products are not generated and output combining is not required. These do not therefore influence or constrain the selection of the transmit/receive frequency pair. However, channel unit cost is reduced if one synthesizer can control channel selection on both transmit and receive; this means transmit and receive frequencies should be correlated in one of the following ways:

- possess a common frequency difference (typically half transponder ≃ 27 MHz) so that second frequency can be derived by mixing synthesizer output with fixed source (existing Telesat Thin Route system)
- be symmetrical about a given frequency, so that desired frequencies are upper and lower sidebands from mixing synthesizer output with fixed source (SPADE system)

Restricting the range of permissible frequencies reduces synthesizer cost slightly but is probably not merited.

For a multi-channel (Type B) earth station, several transmitter options are possible, as discussed in Appendix C. A novel configuration for a 4 channel earth station which minimizes HPA requirements is presented in Figure 2-2.

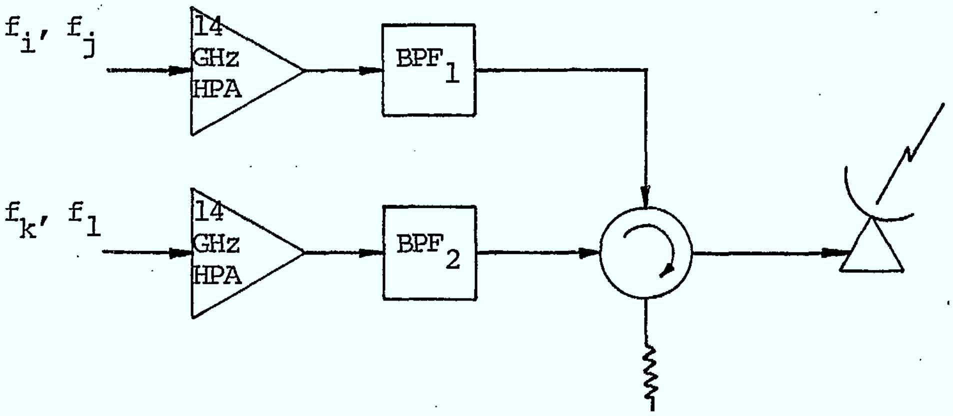


FIGURE 2-2

Two transmit chains are employed, each handling two carriers. This provides parallel redundancy, obviating the need for standby equipment. It also permits the HPA's to be operated at saturation with essentially lossless combining and no illumination of the satellite with 2A-B and higher order IM products produced in the HPA's. This implies very efficient DC power utilization without a distortion penalty.

Simple (few poles) wideband 14 GHz bandpass filters are employed to remove these IM products (without distorting wanted carriers); BPF_2 also provides isolation for combining purposes. Simplicity means both low cost and small insertion loss RF filters possessing a low Q. The scheme relies on sufficient separation of the assigned SCPC frequencies to ensure 3'rd order product energy falls outside the passband of the post-filter and is not radiated to the satellite, as illustrated in Figure 2-3.

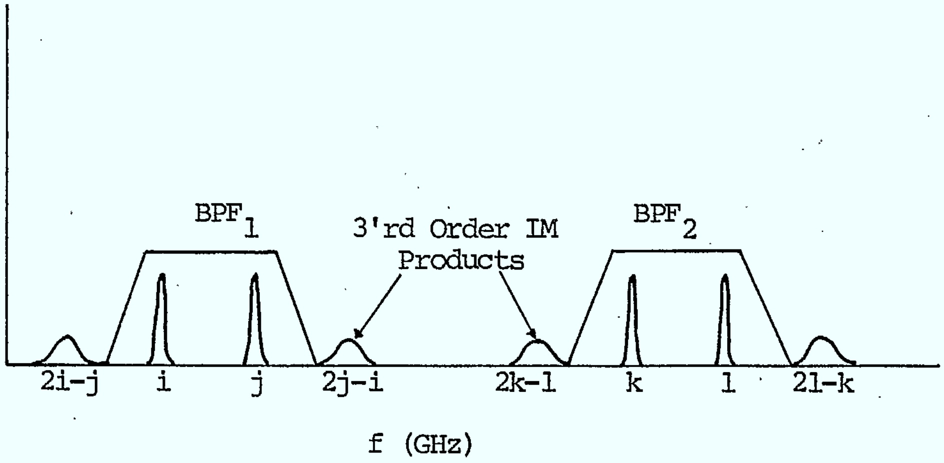


FIGURE 2-3

For a fixed filter bandwidth

$$B \gg \Delta f \quad = \quad \text{SCPC channel spacing}$$

centered on frequencies f_m and f_n respectively $(f_m - f_n| > B)$, we have therefore imposed both upper and lower limits on the assignable frequencies

$$f_m - \frac{B}{2} \leq f_i \leq f_m - \frac{B}{4}$$

$$f_m + \frac{B}{4} \leq f_j \leq f_m + \frac{B}{2}$$

$$f_n - \frac{B}{2} \leq f_k \leq f_n - \frac{B}{4}$$

$$f_n + \frac{B}{4} \leq f_l \leq f_n + \frac{B}{2}$$

For example, with

B ≃ ½ transponder bandwidth assigned to rural service

nearly one half of the channels can be assigned with such a terminal configuration as illustrated in Figure 2-4.

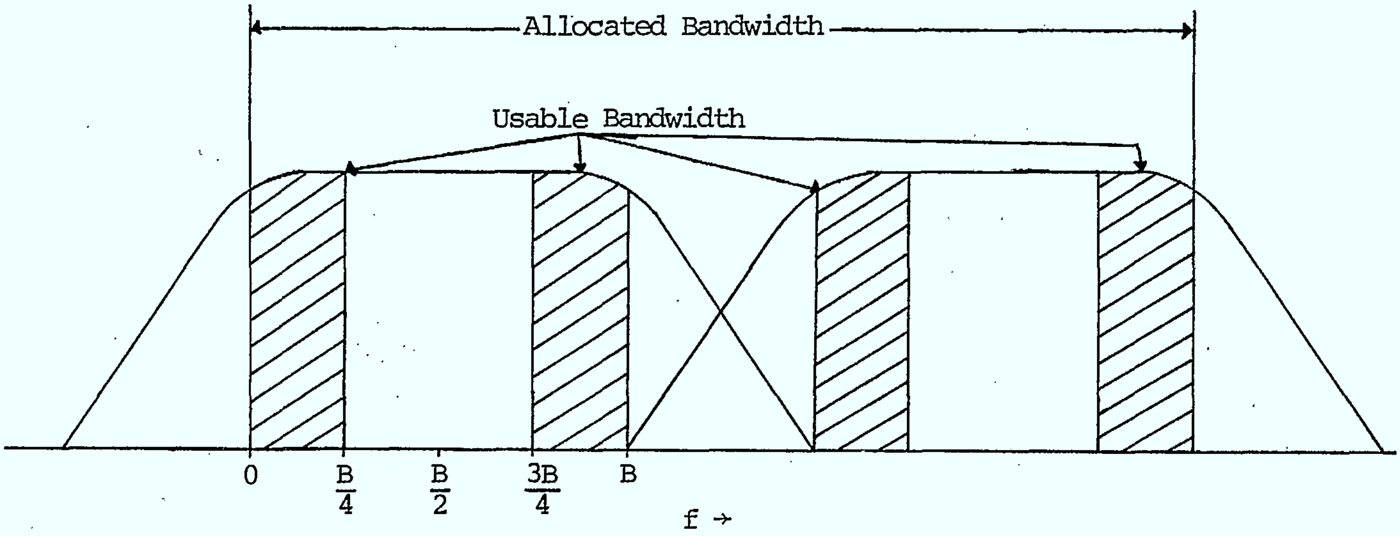


FIGURE 2-4

A value of B less than this reduces the number of SCPC frequencies assignable to the terminal and increases the output filter Q. Note that: (i) The configuration in Figure 2-2 permits capacity to be expanded in units of two channels simply by adding parallel transmit chains. No alteration of existing equipment is required except possibly a change in output filter bandwidth to maintain

B < total allocated SCPC bandwidth/terminal capacity

and corresponding alteration of assignable frequencies. The scheme thus permits graceful growth of a rural terminal from two to eight channels. For more than eight channels a single, backed off HPA, redundantly configured, would be preferred to avoid replication of up-convertors and the increasingly complex frequency plan imposed by the output combiner. (ii) The accessible transmit channels can be altered from terminal to terminal simply by staggering the filter center frequencies to the left or right. This should not be necessary as less than half the carriers (in a hubbed system at least) could at any time be transmitted from multi-channel rural terminals.

Of concern also is the disposition of SCPC carriers over the available transponder bandwidth. The intermodulation noise contribution to received C/N for a homogeneous SCPC system is normally evaluated assuming one of two frequency plans described as follows:

- random selection of carrier frequencies, implying a constant IM product spectral density across the band (plus ripple margin);

- uniform carrier spacing, implying all the in-band IM noise falls on the occupied channels.

As the percentage of unused available transponder bandwidth increases, the IM allocations obtained under these two conditions diverge. In the first case, excess bandwidth is used to advantage in proportionately increasing the average carrier-to-intermodulation noise ratio (C/I). In fact, performance somewhat better than random spacing can sometimes be obtained with specific frequency plans [3,4], although these could be unduly restrictive for our application.

In a homogeneous system there is only the question of which frequencies to select for transmission. In a non-homogeneous system, such as the two level scheme proposed for hubbing circuits through one or more central stations [5], it may also be desirable to specify the power level(s) permissible at each frequency. This could serve the purpose of restricting the type and hence the level of IM interference falling on small carriers, ensuring links to the central station do not become intermodulation noise limited, implying the need for increased EIRP from the rural terminal (an expensive commodity).

Several frequency plans keep IM products of large carriers off the small carriers; one example is the odd-even channel assignment in which large carriers can only appear on even numbered channels [5]. Carrier frequencies within the odd and even channel grouping are best assigned randomly as if two independent homogeneous systems (at the two carrier levels) were being considered.

Factors other than intermodulation may influence the selection of SCPC frequencies in the transponder, although these depend on the specific system and it is difficult to generalize. Coordination with adjacent satellite systems may limit up-link frequencies from the small terminals to some permissible portion of the band. Furthermore, it would almost certainly be necessary to avoid frequencies within the energy dispersal range of adjacent satellite TV carriers [1].

Adjacent channel interference between SCPC carriers is of course an important consideration in the system design; however, it will not affect frequency assignment if the SCPC channel spacing and transmit and receive filters are selected appropriately. Some reduction in channel unit cost may be achievable by increasing the channel spacing-to-symbol rate from the 1.4 value typically employed in (bandwidth limited) SCPC systems. This might in fact be essential for the proposed two level (hubbed) system with odd and even channel spacing, in which a small carrier can be flanked by two large (interfering) carriers.

2.3.2 Voice Activation

It is possible to substantially increase the capacity of an SCPC system by utilizing a voice activation scheme. Voice activation is a method by which advantage is taken of the idle periods that exist in speech. These idle periods are detected and the earth station transmitter is switched off during the pauses in speech. This has two effects that improve the utilization of the space link, namely:

(i) By conserving the transponder power during pauses in speech it is possible to increase the overall number of voice channels simultaneously accessing the transponder.

(ii) The randomness of location of active carriers at any instant in time and the fact they always appear modulated, results in a more favourable intermodulation noise spectrum. For a given number of active carriers, modulation improves the C/I by nearly 10 log (channel spacing/carrier noise bandwidth) $\simeq$ 1.5 dB. This advantage is theoretically offset by some reduction in flexibility of choosing specific SCPC carrier frequencies to minimize in-band intermod; however, in a demand assigned system such frequency plans would not normally be employed.

Voice activation increases the power-limited capacity of an SCPC system (carrying voice traffic only) by a factor of at least 2.5, which corresponds to a voice duty factor of 0.4.

Voice activated operation places somewhat different demands on FM and CPSK channel equipment. Both must provide rapid detection of the voice signal, delay between the voice detector and the carrier-control switch (to prevent clipping of the first syllable of a voice-operated transmission), and similar delay at the demodulator (to permit control of the system squelch operation without clipping of the voice and without permitting noise bursts to reach the output at the end of each voice-operated transmission). These functions are all performed more easily in the digital domain.

Rapid demodulator acquisition and the necessity to insert a carrier/bit timing recovery pre-amble at the beginning of each voice activated RF burst, in addition to voice detection, are the key requirements voice activation imposes on the design of a CPSK SCPC channel unit. An FM demodulator, on the other hand, is neither coherent nor synchronous, and does not require a significant acquisition time.

2.3.3 Demand Assignment

In the context of satellite communications, "demand assignment" is a procedure whereby a common pool of circuits or links is shared by all users according to their individual demand. Hence, a circuit is set up between two ground terminals only when it is necessary. Access to the common pool is usually distributed over several terminals, thus providing Demand Assignment Multiple Access (DAMA). To enable allocation of individual duplex channels, transmission through the satellite is done on the basis of single channel per carrier (SCPC). Hence, a fully interconnective system is possible, with the required switching being performed at the ground terminals by means of channel selection. Since most users usually require access for a small fraction of the total time, the number of ground terminals may greatly exceed the maximum number of simultaneous connections. This results in an enhanced operational efficiency of the satellite resources.

2.3.3.1 Transponder Utilization Improvement

In a comparison of the traffic handling capacity of demand assigned and pre-assigned service for a large number of low-density traffic terminals, Dill [6] has shown that demand assignment yields an improvement factor of five to fifteen. This analysis is relevant to a system such as SPADE [7], [8], [9], in which the satellite serves as a trunk system, interconnecting ground terminals which in turn are accessed by a large number of users. In a rural communications system, the situation is somewhat different in that a remote ground terminal may serve only one user. In such a system, the objective is thus to maximize the number of user locations (telephones) for a given satellite resource, rather than the traffic capacity. Hence, a different measure of improvement must be determined.

Suppose we have N remote telephones and n connecting links (2n RF channels) to the terrestrial network, and that the average demand per telephone during the peak period is d erlangs. The total average demand will be a = Nd. For such a system, the grade of service, or probability of blocking, is given by [6]

$$P_B = \frac{a^n/n!}{1 + a + a^2/2! + \ldots + a^n/n!}$$

Consider first a system having only one link, or n = 1. Hence

$$P_B = \frac{a}{1 + a}$$

from which

$$a = \frac{P_B}{1 - P_B} \simeq P_B \quad \text{(for small } P_B\text{)}$$

Now, since a = Nd, it follows that

$$N \simeq \frac{P_B}{d}$$

or the number of telephones is directly proportional to the grade of service and inversely proportional to the individual demand. Note that for a pre-assigned system, N = n, so that the improvement (increase in number of telephones per link) compared to a pre-assigned system is simply

$$I = \frac{N}{n} = N = \frac{P_B}{d}$$

Assume now that each telephone is used on an average of five minutes during each peak eight-hour period. Thus,

$$d = \frac{5}{8 \times 60} = \frac{1}{96} \text{ erlangs}$$

so that

$$I = N = 96 P_B$$

Thus, for a 5% probability of blocking,

$$I = N = 4.8$$

In general, the number of telephones will be given by

$$N = \frac{a(n,P_B)}{d}$$

and the improvement by

$$I = \frac{N}{n} = \frac{a(n,P_B)}{n\,d}$$

where

$a(n,P_B)$ = the capacity in erlangs corresponding to n links and grade of service P_B.

It is most convenient to determine $a(n,P_B)$ from an erlang Table [10]. From inspection of such a table, it is seen that for values of n greater than about 10, the capacity is not a strong function of the grade of service, providing this is small. Choosing $P_B = .005$, the improvement has been determined for various individual demands and numbers of links, and is shown in Table 2.2.

	Demand, Minutes/8-hr. Period				
n	5	10	20	40	60
10	38.0	19.0	9.50	4.8	3.2
20	53.3	26.7	13.3	6.7	4.4
50	68.9	34.5	17.2	8.6	5.7
100	77.7	38.9	19.4	9.7	6.5
150	81.5	40.8	20.4	10.2	6.8
200	83.8	41.9	21.0	10.5	7.0

TABLE 2.2 - IMPROVEMENT RELATIVE TO PRE-ASSIGNMENT

Note that a system having only 10 links (20 RF channels) could support 32 telephones, used one hour a day during the peak 8-hour period, with a grade of service of .005. Also note that as n becomes large, the improvement tends to level off. Thus, for example, two parallel systems of 100 links each are 93% as efficient as one system having 200 links.

From the above analysis, we readily conclude that DAMA must be an integral component of any cost-effective rural communications system.

Other potential advantages of a DAMA system include the following:

(1) Dynamic up-link power control, further increasing transponder utilization (at the expense of more complicated control).

(2) Automatic dialing and call billing, including access to the terrestrial switched network.

(3) Priority and pre-emption of calls.

(4) Remote monitoring and control.

(5) Accumulation of statistics relating to traffic patterns.

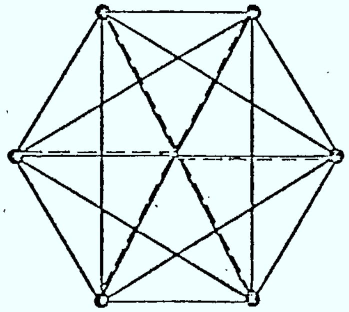
2.3.3.2 Basic Configurations

Werth [9] identifies and discusses three basic configurations which reflect the current DAMA schemes. These are illustrated in Figure 2-5, and are discussed below.

Type 1 - Distributed Control - Full Interconnectivity

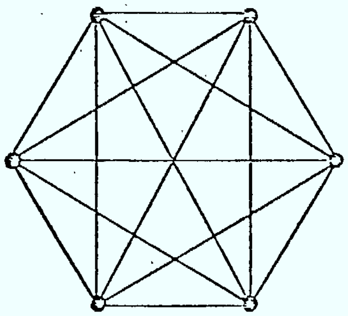
An example of this configuration is the SPADE system [7], [8], [9]. Each ground terminal can obtain a direct connection to any other terminal in the system. There is no central control, and each terminal accesses a Common Signalling Channel on a time share basis, broadcasting to the entire network its requests and call destinations.

In the SPADE system, satellite links serve as trunks between ground terminals located in different countries. Voice is encoded using PCM and transmitted as QPSK. The Common Signalling Channel is a true TDMA network, with a reference burst provided by one station from which all other stations maintain synchronization. The signalling channel occupies a pre-assigned



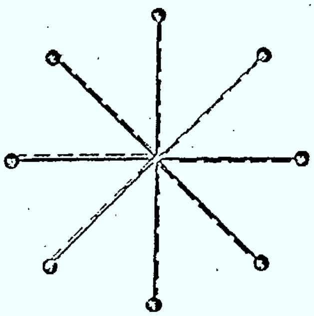
Type 2

Full Interconnectivity and Central Control



Type 1

Full Interconnectivity and Distributed Control



Type 3

No Interconnectivity and Central Control

---	Signalling Channel
..	Earth Terminal (node)
——	Duplex Satellite Channel

FIGURE 2-5 - BASIC DAMA CONFIGURATIONS

frequency slot, and provides 49 one-millisecond time slots in a 50 millisecond frame. Each station is assigned one of these time slots, and during that interval, broadcasts to the network its requests for capacity, destinations, status, and other signalling data. All other stations receive during that time, and respond to properly addressed messages. The channel bit rate is 128 kbps, with a separation of 5 bits between bursts.

Some advantages of a Type 1 system are stated below:

(1) Full interconnectivity eliminates the need for double hops, improving transponder utilization and resulting in less delay, echo problems, and other transmission difficulties.

(2) In an international system such as SPADE, the political and economic implications of one nation having control over everyone's traffic are avoided.

(3) It does not require a central control station, thus decreasing the network's vulnerability to failure or sabotage.

(4) Pre-assigned (rather than random) access to the common signalling channel results in minimum delay in establishing links and exchanging signalling information.

The main disadvantage of this type of system is the terminal complexity. This is clearly a major consideration for a rural system incorporating a very large number of terminals, each serving one (or a few) users.

Type 2 - Central Control - Full Interconnectivity

This type of configuration lends itself to the typical Domestic Satellite (DOMSAT) application, which usually consists of a central ground terminal in a large centre and numerous smaller terminals located in other cities. An example of such a system is the SUDOSAT system being installed in the Democratic Republic of Sudan by the Harris Corporation [10]. This type of system is practical for a network which requires simple equipment at the remote sites and for which there are no political constraints as to the location of the control station. The control station is of necessity quite complex, and in addition, full redundancy is usually provided. Common Signalling can be by means of a time shared (TDMA, random access, or polled) common channel, or by dedicated individual signalling channels.

In the SUDOSAT system, Harris has made the decision to use the dedicated signalling channel approach. This decision was based on cost, reliability, maintainability, and system integrity (the failure of any single TDMA modem could render the entire network inoperable). The Harris implementation uses a narrowband PSK modem operating at 1200 baud. Eight 1200 bps signalling channels require the same power and bandwidth as one SCPC channel, providing a signalling link with a BER of 10^{-5}. Error detection capabilities are incorporated, resulting in a 10^{-22} probability of incorrectly receiving a message.

Some advantages of a Type 2 system are as follows:

(1) Full interconnectivity eliminates the need for double hops.

(2) Remote terminals are relatively simple, reducing costs if a large number are required.

(3) Placing most of the complex control equipment at a central location eases maintenance problems.

(4) A centralized computer system with communication links to the remote terminals provides the capability of remote monitoring and control, such as centralized dynamic up-link power control, selective traffic blocking, etc.

(5) New terminals can be added and other configuration changes made with impact only on the central terminal.

(6) Data is readily available for billing and traffic analysis.

(7) Operator assistance and traffic routing can be provided as required.

The main disadvantages of the Type 2 configuration are the complexity of the central control terminal and the dependence of the entire network on its proper operation. This usually implies central redundancy, further increasing cost. The economic consequence of a central station of course diminishes as the number of terminals in the network becomes large.

Type 3 - Central Control - No Interconnectivity

In this type of system, the remote terminals have no means of interconnection except via the central terminal in a double hop mode. Hence, it is most appropriate for a system in which each remote terminal serves a very small number of users (perhaps one), and in which most of the traffic is between the remote stations and the central station or terrestrial network. Examples of this type of system are the Marisat [12] system and the CRC [13] experimental system. In both cases, the Common Signalling Channel (request channel) is random access, thus introducing the possibility of message collision. (Note that message queueing must be accounted for whenever access to a common signalling channel is on a random basis.) If two messages collide on the request channel, or if errors have occurred, no acknowledgement will be received by the remote terminal, and a new attempt is indicated.

Advantages of a Type 3 system are essentially the same as those of a Type 2 system, except that full interconnectivity is not achieveable. This usually implies a certain amount of double-hopping, and may decrease the utilization efficiency of the satellite.

Similarly, the disadvantages are mainly associated with the complexity, cost, and vulnerability of the central control terminal. In a system with a very large number of ground terminals (and hence a high call rate), random access to the Common Signalling Channel may cause operational difficulties.

2.3.3.3 MCS Cyclic Assignment

A novel approach to demand assignment has been proposed by Miller Communications Systems (MCS) Ltd. which is referred to as Cyclic Assignment Multiple Access (CAMA) because of the manner in which channel assignments are performed. It is described in more detail in Appendix D, and can be classified as Fully Interconnective with Hybrid Control. As this classification suggests, control is partly centralized and partly distributed. The main area of innovation relates to the channel assignment protocol, which is more rigidly defined than in other systems, thus reducing the amount of message transaction, real-time processing, and intervention by the central control terminal. This allows distributed control (with monitoring plus minimal central control) without increasing the complexity of the remote terminals, while greatly decreasing the complexity of the central terminal. All messages are direct from terminal to terminal, and there is no need for relaying of messages by the central control terminal. As described in Appendix D, at any given time, the channel pair to be next assigned is used as a Common Signalling Channel in a random access fashion. When this pair has been assigned to the first to request it, all other terminals move onward to the next unused pair, which then becomes the Common Signalling Channel. The central control terminal monitors activity (for billing, traffic analysis, etc.), authorizes entry to the system, and indicates by means of a transmitted carrier the next pair of channels to be assigned. This system appears to have potentially all the advantages of a Type 2 system, but with considerably simpler central control requirements.

Other advantages of this system include the following:

(1) The de-emphasized role and minimal complexity of the central control terminal result in degrees of flexibility beyond those of conventional DAMA systems. For instance in a rural system, several central control terminals could be provided, each defining a particular rural area, and acting as gateway terminals to the terrestrial network. A given system could start off very modestly and be upgraded as warranted by traffic requirements. Similarly, an evaluation system (or pilot project) could be implemented at

much less expense than a conventional central-controlled system. Werth [8] concludes that "The technique of initiating service with pre-assigned operations and of slowly progressing from that mode to full DAMA will be the key to success". Cyclic Assignment appears to be ideally suited to this technique.

(2) Constant movement of the signalling channel makes this system less vulnerable to intentional or accidental jamming than a system using pre-assigned (fixed) common signalling channel(s). This concern was reflected in [14], which advocated dynamic reassignment of the control channels to minimize their vulnerability. Further security is achievable by: (i) disguising the marker carrier (i.e., the location of the signalling channel at any time) by employing appropriate message codes, (ii) varying the position of the signalling channel with respect to the marker in a manner known only to the participating terminals.

(3) Due to the decreased amount of message transaction and processing required to complete an assignment, assignment time should be reduced, resulting in lower probability of request contention, queueing, etc. than for the conventional system with random access. Also, fewer messages means lower probability of error. This should result in an improved grade of service.

A possible disadvantage of this system is that for some fraction of the total time (depending on the call rate) request messages are precluded due to the necessity for the remote terminals to seek and follow the indicated channel. This "unavailable" time will result in an increased request density during the "available" time, increasing the probability of message contention, particularily at high call rates. An accurate comparison (grade of service, flexibility, complexity, cost, etc.)with other systems has not been performed, and indeed this could only be done subject to a given set of specific requirements. (To a large extent, such requirements would be dependent upon the interfacing terrestrial system and authority). Although this system may not compare favourably under conditions of very high call rate (such as SPADE), it is thought to compare quite favourably with other systems using a random access Common Signalling Channel. Hence, it is worthy of further consideration as an alternative to conventional DAMA, and is considered to be a prime candidate for a rural communications system.

2.3.4 Up-Link Power Control

A significant detrimental effect of utilizing the 12/14 GHz band and higher for satellite communications is the increased fade depth encountered on the satellite to earth station radio path due primarily to rainfall. There are basically three approaches to the solution of this problem:

1) Increase the fade margin allowance,
2) Use an adaptive compensation scheme,
3) Use site diversity.

The brute force method of applying larger fade margins and its resulting effects are discussed in Appendix B.

Earth station diversity has received attention as a means of alleviating the effects of fading [15]. The problems associated with this approach, however, are:

1) The spacing between diversity stations must be tens of kilometers*.

2) Increased earth segment costs through hardware duplication.

3) Synchronization and control problems.

4) The requirement for a backhaul link between diversity stations.

5) The cost of diversity must be borne even during seasons when heavy rainfall is not prevalent.

---

[*] Based on the strong tendency for heavy rainfall to be localized rather than distributed over a wide area.

Clearly, large scale site diversification for a rural satellite system would be impractical because of the costs.

For a hubbed network, the provision of more than one hub or gateway station per spot beam (not necessarily interconnected by a dedicated backhaul link) would constitute a form of site diversity and might reasonably be considered in a DAMA-based network. In this case the centralized DAMA controller would serve to direct calls to the most appropriate gateway station considering its location, propagation conditions, and available channel equipment. Even with pre-assigned SCPC channels, splitting traffic from a multi-channel rural terminal to more than one gateway would provide some diversity.

In the category of adaptive compensation schemes, power control in the transmitting earth station has been proposed to compensate slow variations in up-link path loss [15]. Adaptive power control in the satellite to compensate down-link variations is also feasible [17,18] but complicates the design and operation of the satellite transponder, and is not in any event an option with Anik C. Discussions here will therefore be limited to the use of up-link power control in the transmitting earth stations.

For a backed-off SCPC/FDMA system with a moderate number of accesses, each one receiving only a small fraction of the SCPC traffic, considerable benefit can be derived from the use of up-link power control. Up-link <u>and</u> down-link fades are compensated simultaneously by maintaining constant carrier power into the receive earth stations [19]*. While individual carrier power levels into the satellite will vary,

---

*For earth station receiver noise dominated links the received C/N loss (fade) equals the reduction in received carrier level. Maintaining a constant received carrier level is therefore equivalent to maintaining a constant C/N.

the statistical independence of down-link fades to different locations implies that variations in multi-carrier TWT operating point will be small.

The use of up-link power control enables fade margins in a fully connected SCPC system to be reduced from 7-10 dB to 2-4 dB depending on rainfall statistics, desired availability, number of accesses, and accuracy of the fade estimator. This implies a 5-6 dB reduction in average transmitted power from the earth station and a corresponding reduction in off-axis interference to adjacent satellites. Note, however, that up-link power control does not effect a reduction in the earth station HPA capacity since the peak transmitted EIRP will still be required under maximum fade conditions.

Difficulties arise, however, in the implementation of up-link power control since a transmitting earth station must have knowledge of its up-link fade and the down-link fades at each earth station to which it is transmitting. In devising a practical scheme to accomplish this, measurement accuracy, system stability and cost must be considered.

There are basically two approaches to the implementation of up-link power control:

(a) centralized control
(b) distributed control

Furthermore, power control can be applied to all or some portion of the active SCPC links without affecting the advantage derived on these links, providing the basic requirement for a large total number of accesses is satisfied.

With centralized control, decisions about transmit powers are made and distributed from a central location such as the gateway station and with distributed control, each pair of earth stations terminating a duplex circuit selects their own transmit powers. Centralized power control in a fully connected, demand assigned SCPC system is complicated and impeded by extensive communications requirements, and would be costly to implement. Distributed control schemes, though somewhat simpler, may suffer performance limitations and in particular, demonstrate unstable behaviour, although this has not been verified [20].

One simple form of distributed control which merits attention is described as follows. First of all, power control need not be applied for channel request and assignment since coding can provide satisfactory margin at little expense in overall efficiency. Once they have been assigned channels, two stations begin transmission at nominal (i.e., low) power. If receive performance at either end is below the desired operating limit, a tone (or other form of signalling) is activated in the local transmit baseband, to be removed when the remote station increases its carrier level sufficiently. This long (2 satellite hop $\simeq \frac{1}{2}$ second delay) control loop could be activated briefly as part of call set-up, or operate continuously throughout the call. In the latter case, the control signal must not interfere with the voice signal, yet be strong enough to penetrate a heavily faded link (if the received carrier is faded, the transmit carrier is likely faded also). The additional circuitry required to implement the scheme is not great, providing a performance monitor is already fitted at the terminal. This performance monitor would enable/disable a tone generator; a tone detector would in turn enable/disable the slow removal of attenuation on the IF transmit path. The scheme is illustrated in Figure 2-6.

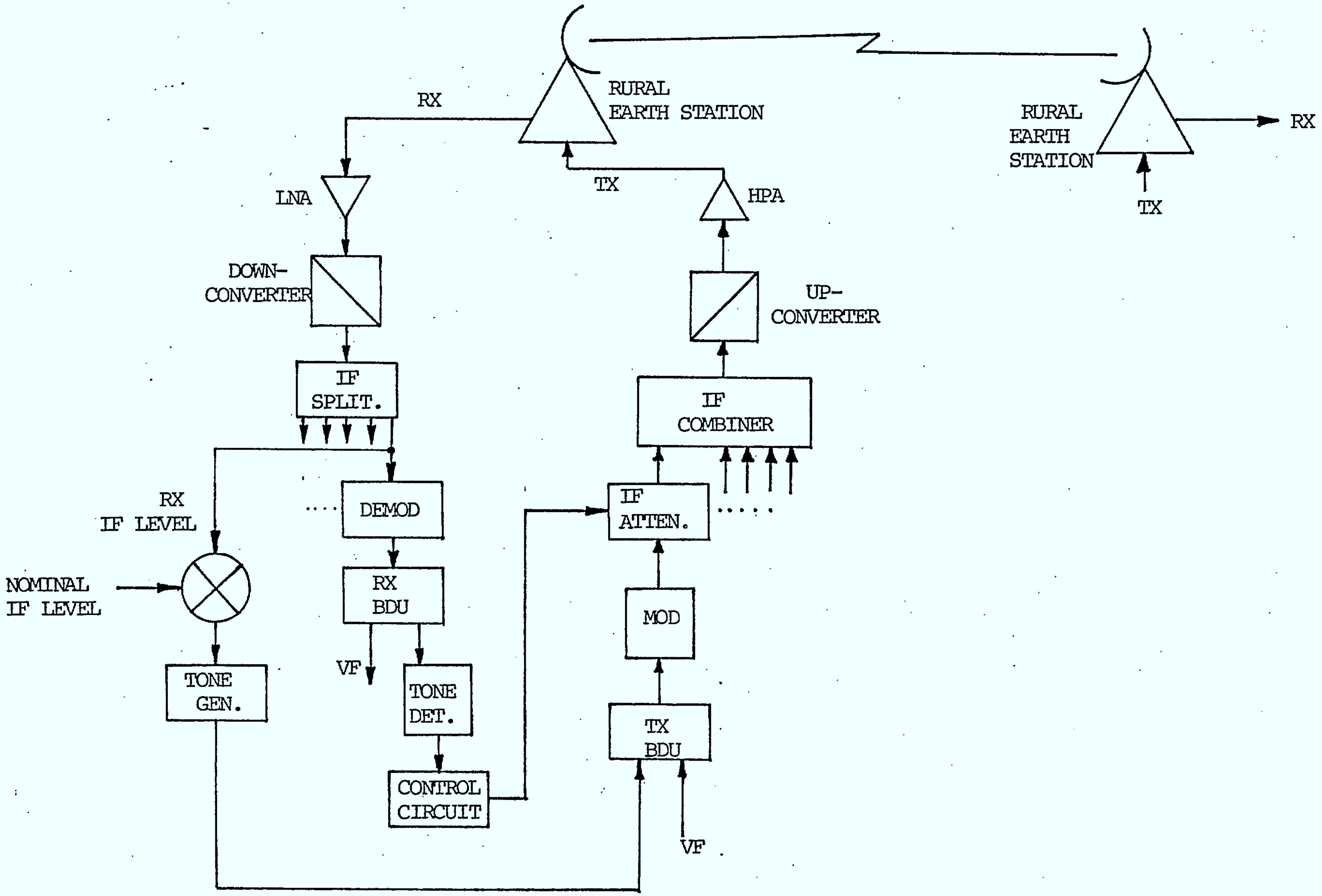


FIGURE 2-6 UP-LINK POWER CONTROL SCHEME AT THE RURAL EARTH STATION

A very simple form of centralized power control for a two-level hubbed system is illustrated in Figure 2-7. Only carriers emanating from the hub are subject to power control; therefore power control does not enter into the design of the rural stations. The two difficulties of centralized power control - namely detection and distribution of fade information - are overcome with little penalty in performance as follows:

(i) Each duplex channel includes a link from a rural station to a hub and a return link from the hub to the rural station. The small carrier transmitted from the rural station is fixed (not subject to power control) and includes a full (typically 7 dB) fade margin allowance. The hub can therefore estimate propagation fades directly from received carrier levels and adjust transmit carrier powers appropriately. Thus carrier levels from the hub are independently controlled by an equal number of received carrier levels, and are up-graded only as required to compensate real fades.

Any common reduction in received carrier powers at the hub due to a down-link fade will be mirrored by increases in transmit powers; however, this common (i.e., correlated) change will be cancelled by the up-link fade, leaving carrier powers at the satellite input statistically independent. Therefore the hub to the rural station links derive the full advantage (4-6 dB) of power control; since these normally absorb about 80% of the satellite power, the overall power limited capacity of the two level SCPC system is at least doubled without any alteration to the rural station.

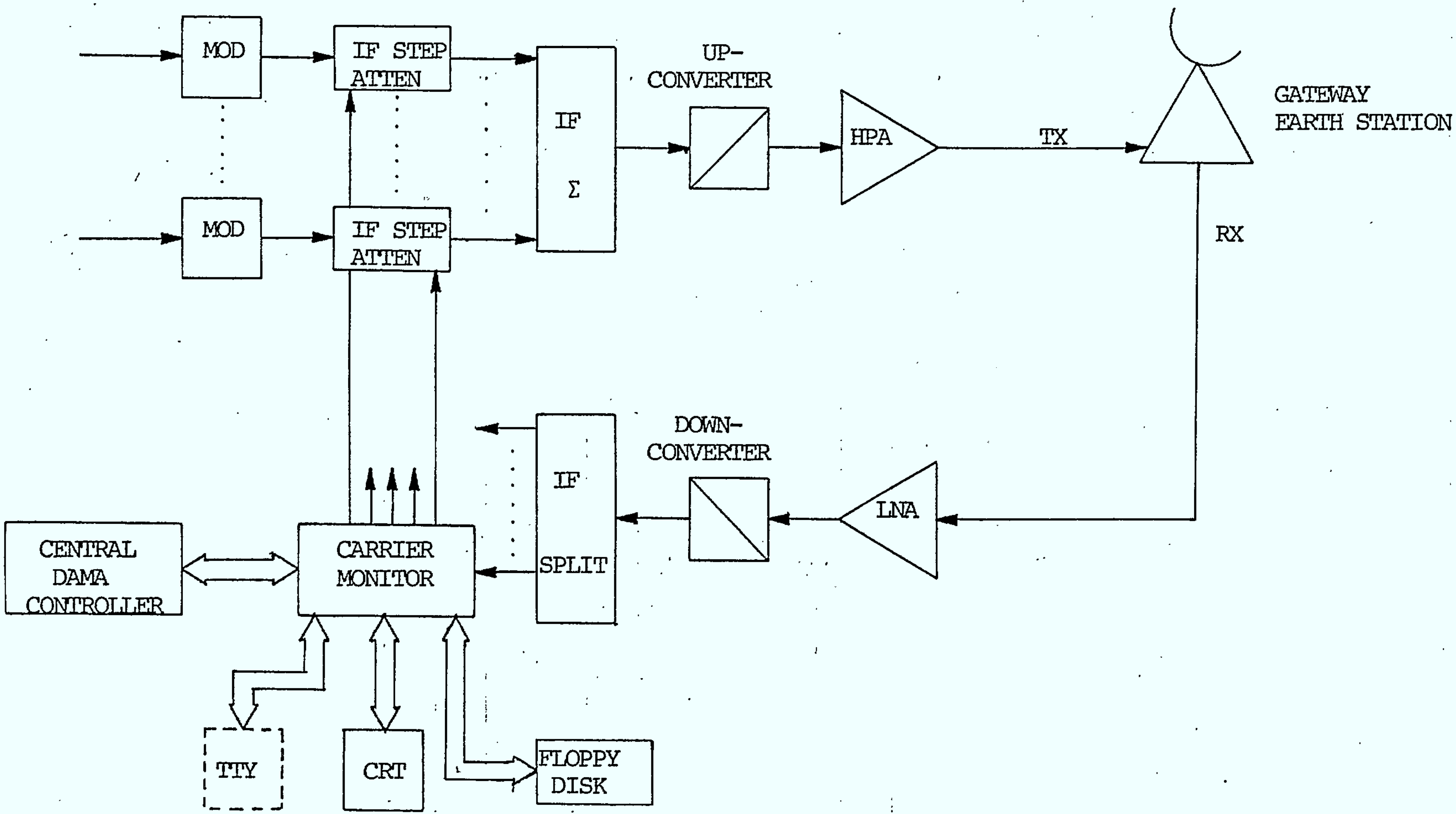


FIGURE 2-7 UP-LINK POWER CONTROL SCHEME AT THE GATEWAY EARTH STATION

(ii) Detection and distribution of fade information are of course greatly simplified in this scheme. Only the hub need possess fade information, and these are immediately available to the desired ± .5 dB accuracy [6] (even with voice activated carriers) and speed (1 sec. sweep rate) from a computer-controlled spectrum monitoring system of the type now being developed for operational deployment [22]. Such a system would likely be in place for monitor, alarm and control purposes in at least one station (e.g., gateway) per spot beam, so it need not represent an incremental cost to the power control system.

If such is the case, the only additional hardware associated with this power control scheme are the IF step attenuators, one per transmit channel unit, plus common control circuitry and computer interface. The key to system effectiveness then becomes the software which processes the carrier level measurements, estimates the return fade, and controls the attenuators. Initially it is proposed that carrier power be adjustable (up to some allowable maximum, say + 6 dB) by an amount equal to the estimated received fade, which is simply the measured carrier level less a constant, in steps not exceeding 0.5 dB [6]. Smaller steps might in fact be necessary to ensure satisfactory demodulator performance in the presence of power control induced amplitude jumps.

Improved return fade estimates could perhaps be made by discriminating between remote up-link and received down-link fade components* and applying

---

*This could approximately be done by extracting the common factor in measured received fades and attributing it to the common down-link.

$$20 \log (14/12) = \pm 0.67 \text{ dB } (1.36, .735)$$

correction factors respectively as illustrated in the following equation (H = hub, S = satellite, R = rural):

$$\text{fade}_{H \to S} + \text{fade}_{S \to R} \simeq .735 \text{ fade}_{R \to S} + 1.36 \text{ fade}_{S \to R}$$

However, some decorrelation between 12 GHz and 14 GHz rain fades on a satellite slant path means the full 0.5 dB improvement in rms estimate accuracy possible by applying the previous equation may not be obtained in practice.

Considerable engineering effort would be required to design, implement, test, and optimize (under operational conditions) even the simple power control schemes introduced here. However, the potential advantage in terms of both satellite power utilization and interference to adjacent satellites clearly indicate that such effort could result in more economic systems.

2.4 Channel Equipment

SCPC channel equipment is typically comprised of (Figure 2-8):

1) One or more channel units (each channel unit incorporates one or two frequency synthesizers depending on whether paired or unpaired frequencies are used - see discussion in 2.3.1).

2) The Common Equipment
   - Transmit IF Combiner
   - Transmit IF Amplifier
   - Receive IF Amplifier (AFC)*
   - Receive IF Splitter
   - Time/Frequency Unit (TFU)
   - DAMA Controller
   - Power Supplies
   - Metering and Alarm Unit

3) VF Jackfield

The function of the channel unit is to :

1) Transmit Side
   - Accept and delta encode or compress and pre-emphasize a voice channel from a terrestrial interface
   - Modulate the processed signal onto an IF carrier generated from the IF transmit frequency synthesizer

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*AGC may or may not be provided.

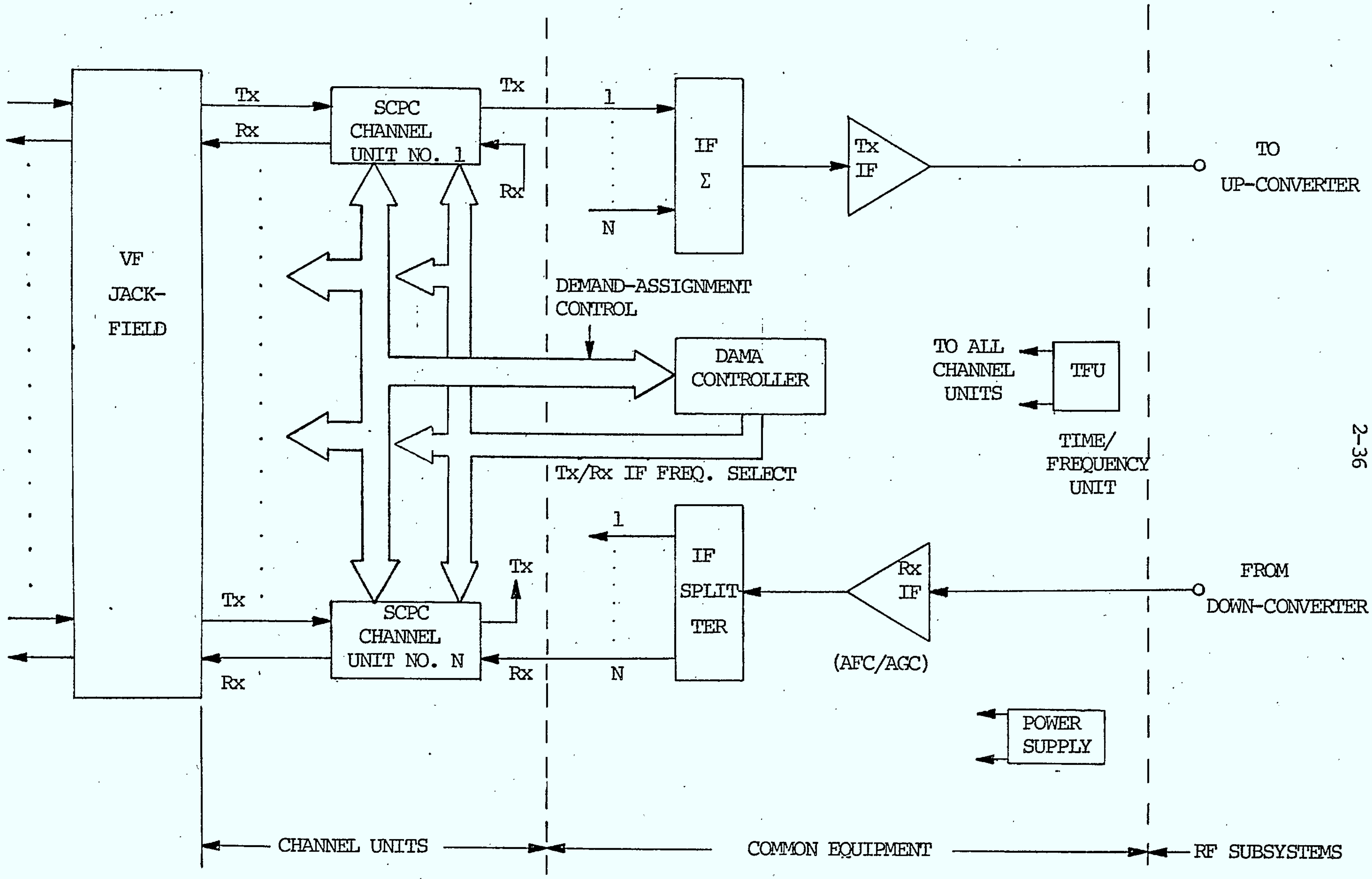

FIGURE 2-8 - SCPC CHANNEL EQUIPMENT CONFIGURATION

2.4.1 Δ-Mod SCPC Channel Unit

Figure 2-9 illustrates the functional block diagram of a typical variable slope Δ-mod channel unit with voice-activation.

The key elements of this block diagram are:

- Variable slope delta codec - an analog-to-digital encoding/decoding scheme which provides a companding effect analogous to that achieved in the analog case (companded FM).

- CPSK modem - the demodulator section may require the presence of a preamble to facilitate carrier and bit timing recovery on voice-activated bursts (Δ-mod unlike PCM does not require frame timing).

- Digital or analog voice detector - used in conjunction with the digital delay line and preamble generator to achieve voice-activation of the IF carrier.

With regards to the incorporation of an echo suppressor function, the existing voice detector in conjunction with appropriate comparator circuits, time constants, delays and break-in circuitry can be designed to meet or exceed the CCITT Rec. G.161 for echo suppressors.

Digital SCPC channel equipment has been manufactured by General Electric, Raytheon Canada, Digital Communications Corporation (DCC), SED Saskatoon, Nippon Electric (NEC), and Fujitsu. Miller Communications (MCS) is currently developing similar equipment for mobile UHF satellite terminals.

Representative of this group of manufacturers' equipment is DCC's STAC (STand Alone Channel Unit) which was specifically designed for thin route applications (a few channels per

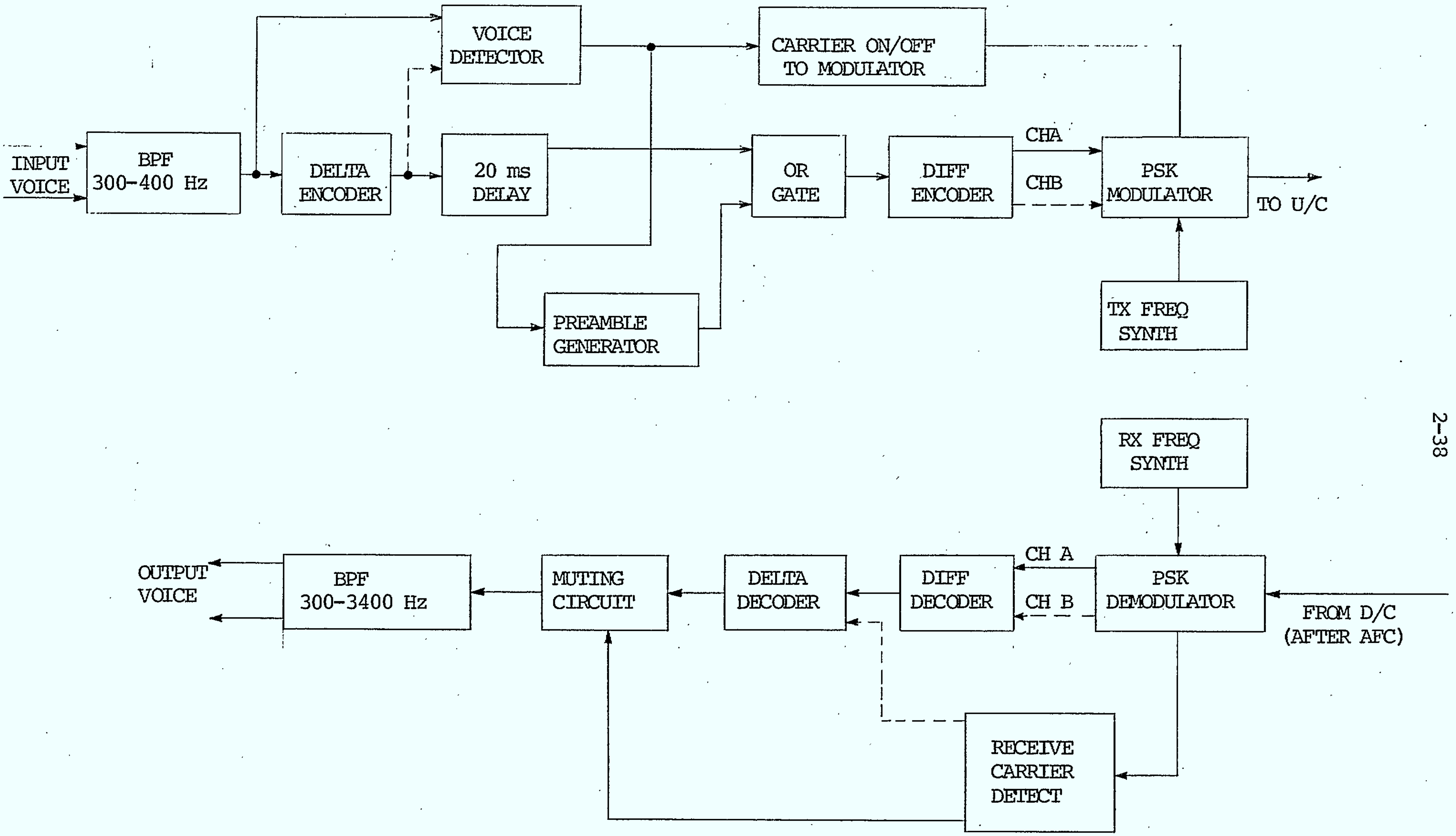

FIGURE 2-9 - VARIABLE SLOPE DELTA MOD SCPC CHANNEL UNIT FUNCTIONAL BLOCK DIAGRAM

2) Receive Side

- Select the required receive IF carrier by means of the IF synthesizer
- Demodulate the IF carrier
- Perform the inverse signal processing of the transmit side and output the resulting voice signal to the terrestrial interface

Thus one channel unit is required for each duplex circuit.

Additional functions which might be incorporated in the channel unit include:

- Voice-activation of the IF carrier
- Echo suppression (according to CCITT Recommendation G.161)
- Multiplexing of low rate data with the voice
- Signalling conversion

The channel unit(s) interfaces with the IF Common Equipment. On the transmit side, the latter combines the output of the channel unit(s) in the IF combiner and amplifies the resulting signal before routing it to the up-converter.

On the receive side, the IF subsystem accepts the IF signal from the down-converter, centres the receive SCPC spectrum (AFC), may perform amplification (AGC) and provides a number of output feeds (IF splitter) for the channel units.

For the remainder of this section, discussions will be directed towards SCPC channel units incorporating (i) variable slope Δ-mod with PSK modulation; (ii) pre-emphasized companded FM.

earth station). Much of the common equipment was incorporated into the channel units to produce a less complex and therefore less expensive stand-alone installation. For larger installations, however, this approach would be more expensive than a common equipment approach.

STAC options include:

- 32/40 kbps delta modulation codec
- 2-phase or 4-phase CPSK
- Carrier spacings of 22.5 kHz, 45 kHz (Intelsat standards) or to order
- Voice-activation (optional)
- Interface modules for E&M or SF signalling
- Echo suppressor (optional)
- Digital multiplex option for simultaneous transmission of Δ-mod voice and data (1200 to 9600 bps) or telegraphy (50 to 300 bauds)

The development of all-digital SCPC channel equipment has also been reported by Harris Electronics Systems and I.T.T.

The Harris all-digital channel unit includes the following:

- 16 kbps adaptive delta modulation (ADM) codec on a single monolithic integrated circuit chip*
- Forward-acting error correcting (FEC) codec
- All-digital demodulator (10 bps to 100 kbps)

---

*Currently available from Harris in either the 16 kbps encoder/decoder version (HC-55516) or 32 kbps encoder/decoder version (HC-55532) at a cost of approximately C$44.40 (qty. 1) or C$32.40 (qty. 100). Similar IC's are available from Motorola (MC 3418-38 kbps) and Consumer Microcircuits (FX 209).

Unique features claimed for the adaptive delta codec include:

- Extremely low power consumption (less than 5 milliwatts)
- very low cost
- increased reliability (monolithic chip realization)
- small size
- stable operation

In Canada, considerable effort has been and is being directed towards the development of similar equipment, e.g., MUSAT channel unit. Significant aspects of the channel unit as they relate to the possible deployment of Canadian technology in a rural satellite communications environment include:

- The development of an adaptive delta codec in a hybrid LSI form (for application primarily at 16 kbps).
- The development of a fast frequency shift keying (FFSK) modem* capable of operating at either 2.4 kbps or 16 kbps.
- The development of a DAMA controller for the channel unit.

While 16 kbps delta is incapable of providing network or international quality voice circuits, the existence of research and development within these areas is significant in itself and an extension to the development of higher bit rate (e.g., 32 kbps) delta codecs and FFSK modems should not be difficult to achieve.

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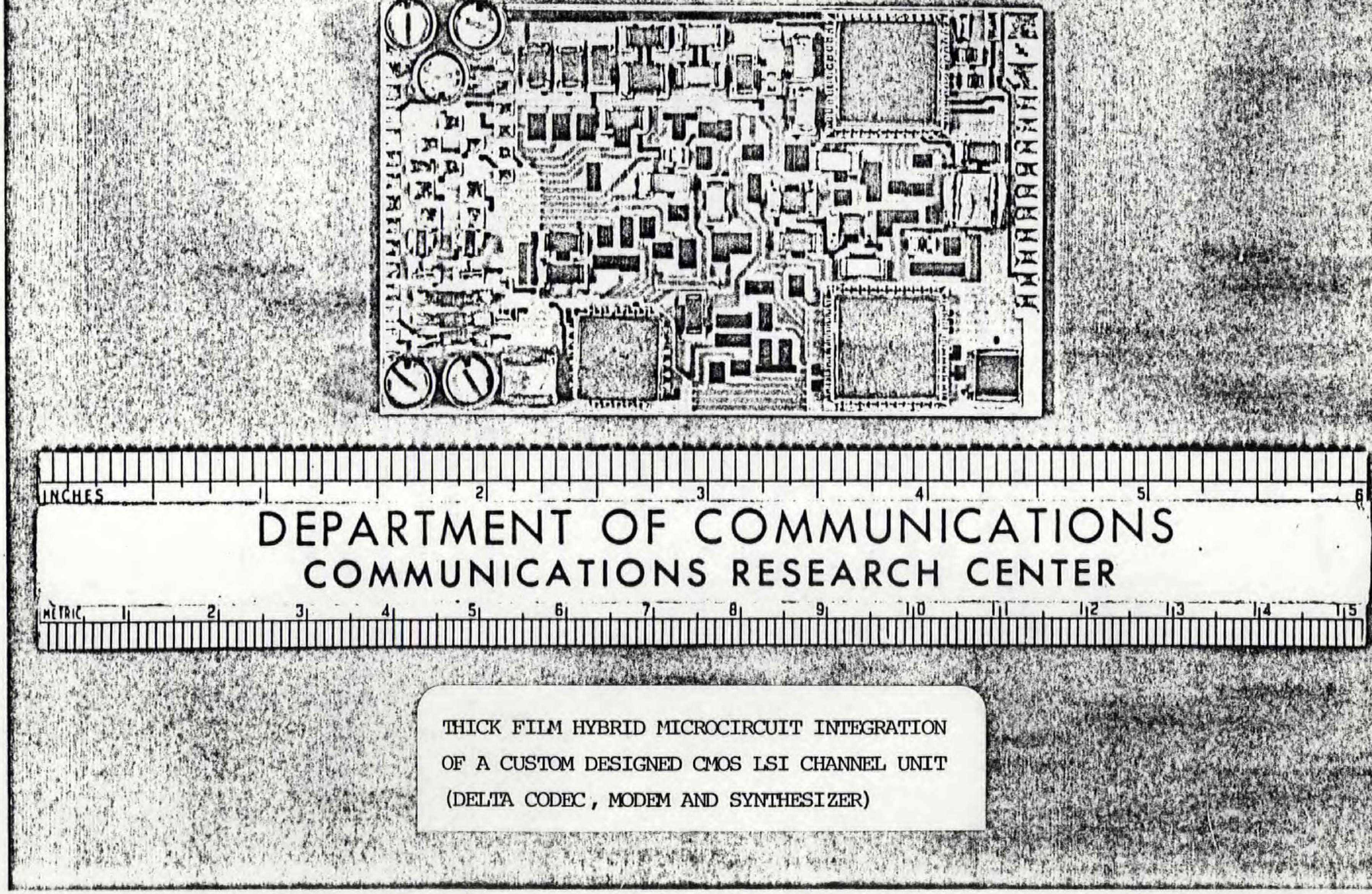
*It is understood that development is also progressing towards the implementation of a 16 kbps FFSK modem in LSI form which should be available within the near future. A developmental model of this type of channel unit is depicted in Figure 2-9.



THICK FILM HYBRID MICROCIRCUIT INTEGRATION
OF A CUSTOM DESIGNED CMOS LSI CHANNEL UNIT
(DELTA CODEC, MODEM AND SYNTHESIZER)

FIGURE 2-9

2.4.2 FM SCPC Channel Unit

Figure 2-10 is a functional block of a pre-emphasized, companded FM SCPC channel unit with threshold extension demodulation and voice activation.

The key elements of this block diagram are:

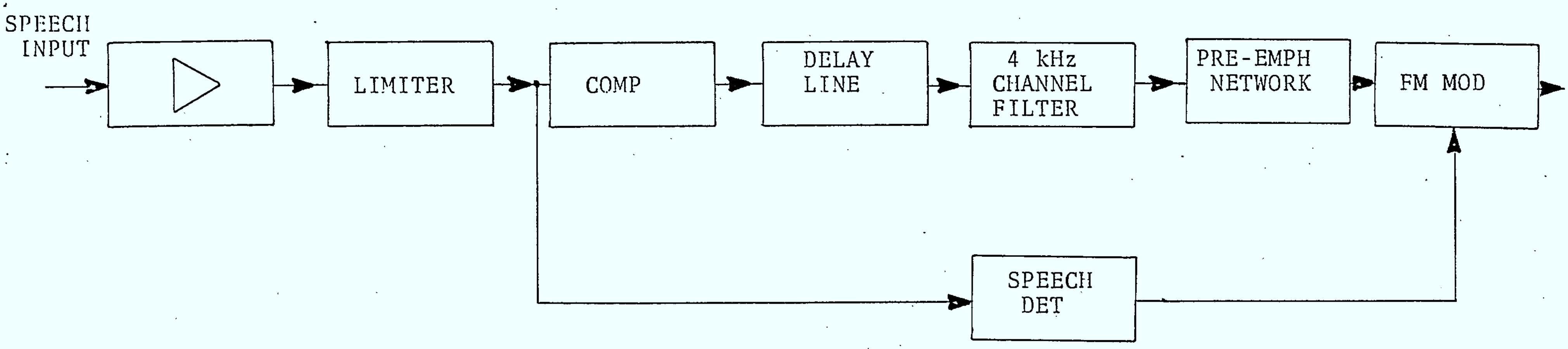
- Deviation limiter - for keeping the peak carrier deviation within the nominal IF passband of the demodulator.
- Pre-emphasis/de-emphasis networks - for flattening the noise spectrum at the output of the demodulator.
- Compressor/Expandor (Compandor) - for reducing the subjective circuit noise level.
- Speech detector - for voice-actuation of the IF carrier.
- Threshold Extension Demodulator (TED) - for extending the operational range of the FM demodulator to lower carrier-to-noise density ratios (C/N_o).

An echo suppression function can also be incorporated in the FM channel unit and is a feature offered by some manufacturers.

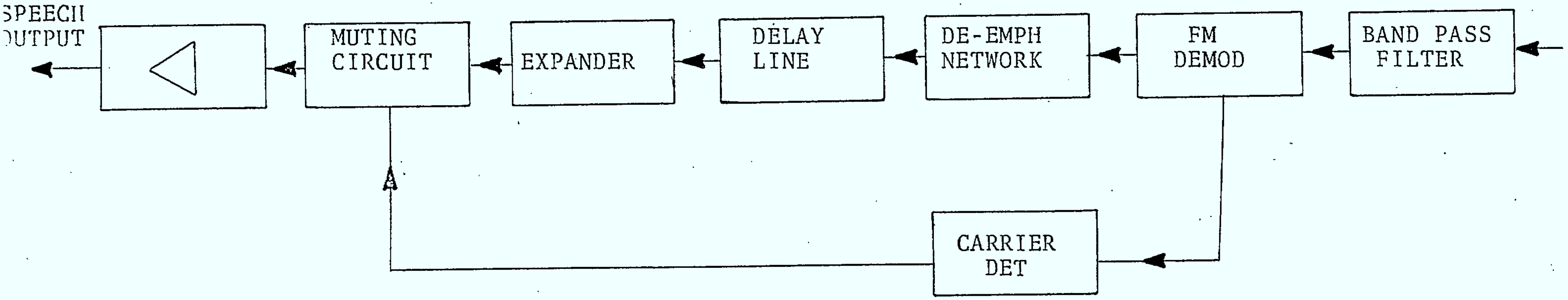
FM SCPC systems have been manufactured by Hughes Aircraft, California Microwave, Scientifc Atlanta and Spar Technology. Several systems are eigher in use or planned for domestic satellite systems, e.g., Algeria, Indonesia, Alaska and Nigeria.

California Microwave's FM SCPC channel equipment (Figure 2-11) is representative of this class of commercially available equipment and includes:

- Pre-emphasis/de-emphasis (pre-emphasis advantage of 6.3 dB).



A) TRANSMITTER



B) RECEIVER

FIGURE 2-10 - FM-SCPC CHANNEL UNIT FUNCTIONAL BLOCK DIAGRAM

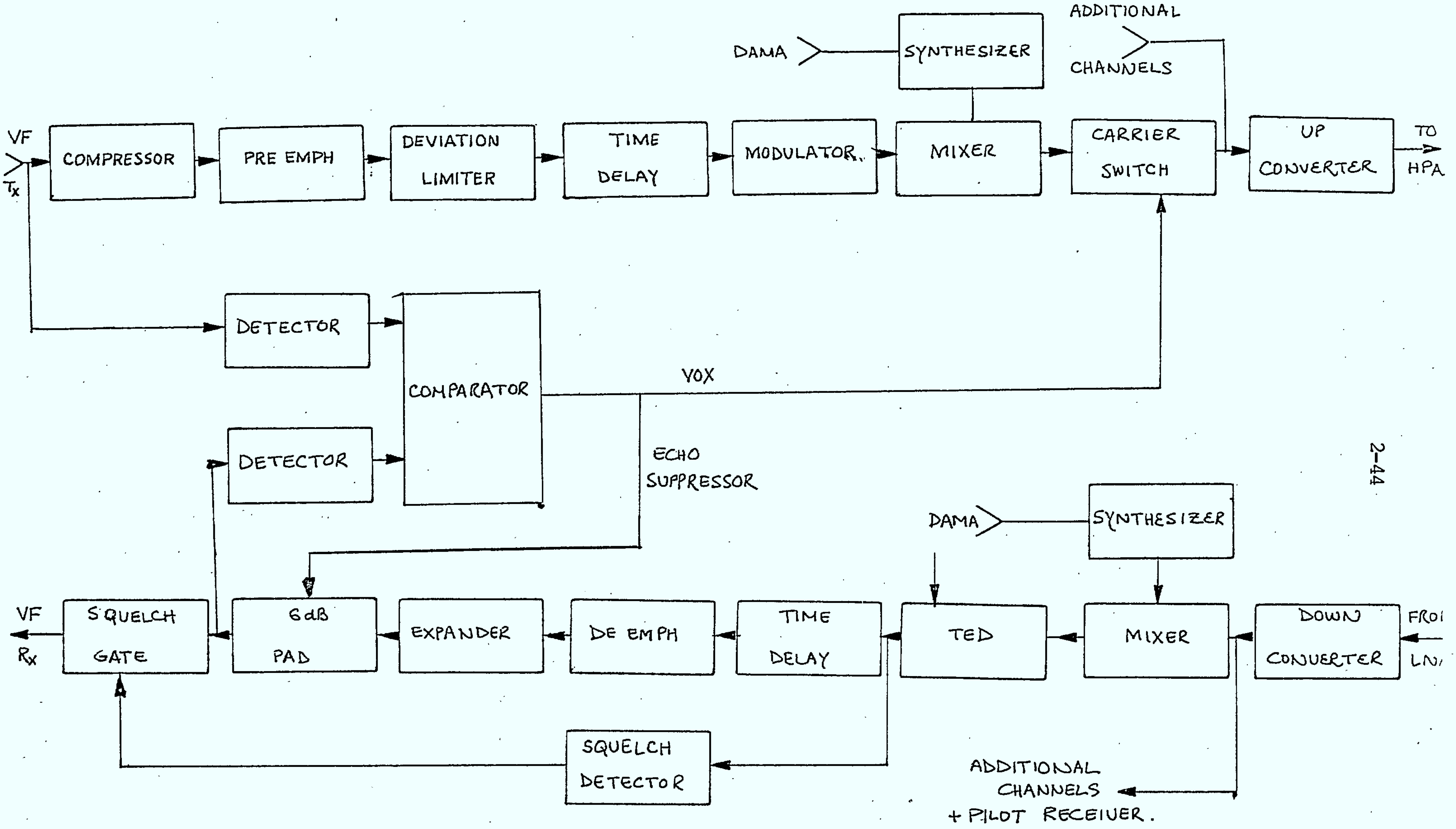


FIGURE 2-11 - CALIFORNIA MICROWAVE'S FM-SCPC CHANNEL UNIT BLOCK DIAGRAM

(a) Crystal Oscillator (Spec. as per HP 10544A)

Diurnal variation (7×10^{-9}) = 17.5 Hz

Long term aging (5×10^{-10}/day) = 1.25 Hz/day

(b) Cesium Oscillator

Long term (better than 10^{-10}) = 0.25 Hz

The weight and power penalties associated with this type of spacecraft hardware remain to be assessed.

- Compandor (2:1 and 1:2 logarithmic compression/expansion laws).
- Voice-activation.
- Echo suppressor (meets CCITT Rec. G.161).
- Threshold extension demodulator (C/N threshold ≅ 6.5 dB).
- Demand assignment capability.

2.5 Frequency Stability and Control Techniques

Frequency control of SCPC systems is necessary for two reasons:

(a) To ensure separation of channels and prevent adjacent channel interference (ACI).

(b) To ensure that the frequency offset of the carrier does not exceed the demodulator pull in range and allows acquisition within one or two milliseconds (for voice activated operation).

This section examines:

(a) Sources of frequency error in SCPC systems.

(b) Effects of frequency error.

(c) Presently used techniques for minimizing these errors including their limitations and costs.

(d) Novel techniques for frequency control.

(e) Estimates of cost savings per station if techniques in (c) above are implemented.

2.5.1 Sources of Frequency Error in SCPC Systems

Each modulated carrier in an SCPC system has a unique nominal frequency associated with it at every stage in the transmission path. The carrier is defined to have a frequency error of Δf when the actual frequency and the nominal frequency differ by Δf.

Frequency errors can arise via the following mechanisms:

(i) Errors in the earth station transmit frequency (f_t).

(ii) Errors in the satellite translation oscillator (f_{sat}).

(iii) Errors in the earth station receive translation oscillator (f_r).

(iv) Errors due to up-link and down-link Doppler shifts.

For geostationary communications satellites, Doppler shifts are assumed to be negligible.

Denoting the demodulator input frequency by f_d, the demodulator input frequency error is given by

$$\underline{\Delta f_d = \Delta f_t + \Delta f_{sat} + \Delta f_r} \tag{1}$$

or for the worst case where all components have the same sign

$$\underline{|\Delta f_d| = |\Delta f_t| + |\Delta f_{sat}| + |\Delta f_r|} \tag{2}$$

In equations (1) and (2), two distinct components of frequency error are present:

(a) <u>Common Frequency Error (CFE)</u>

Δf_{sat} and Δf_r are common to all carriers being transponded via the satellite and received by a given earth station. For a hubbed system, Δf_t is also common except at the gateway station.

(b) Unique Frequency Errors (UFE)

Δf_t is unique to carriers originating from a particular earth station assuming, as is normally the case, that individual earth stations have uncorrelated transmit frequency errors.

The magnitude of the above components of error in any given oscillator is principally a function of:

(a) Initial setting accuracy.
(b) Oscillator aging.
(c) Supply voltage variations.
(d) Operating temperature variations.

In order to compensat for frequency errors arising from aging, periodic readjustment of earth station oscillators is necessary. Errors due to voltage and temperature variations are not normally correctable by periodic maintenance since they tend to manifest themselves in the shorter term; i.e., hourly or daily, and are non-cumulative.

In the spacecraft the situation is similar for voltage and temperature induced variations; however, it is not current practice to periodically readjust oscillator frequency to compensate for aging effects. For present day communications satellites the implications of uncorrected frequency errors over the mission lifetime must be taken into account.

Table 2.3 shows representative frequency stability specifications for modern high stability oscillators. All of these could be considered as candidates for use in earth stations.

Table 2.4 shows frequency stability specifications for current satellite local oscillators.

OSCILLATOR TYPE	STABILITY (Δf/f)			PRICE $ US	COMMENTS
	Temp. (0° – 50°)	Aging (per day)	Voltage ±10%		
VECTRON CO 252-3	$\pm 1 \times 10^{-7}$	1×10^{-8}	NS	500	VHF crystal oscillator, temperature compensated TCXO.
VECTRON CO 224	$\pm 1 \times 10^{-7}$	1×10^{-8}	NS	400	Most stable VHF crystal oscillators; Oversized.
HP 10544A 5 MHz	7×10^{-9}	5×10^{-10}	1×10^{-10}	600	Most stable 5 MHz crystal oscillator; Oversized.
HP 5061 CESIUM	1×10^{-11}	5×10^{-12}	NS	10,000	Atomic standard.

TABLE 2.3 – STABILITY OF MODERN HIGH STABILITY OSCILLATORS

SATELLITE	f_{LO} MHz	STABILITY ($\Delta f/f$)			LIFETIME ERROR
		Temp.	Aging	Voltage	
ANIK A	2225	$\pm 5 \times 10^{-6}$	$\pm 6 \times 10^{-6}$	$\pm 4 \times 10^{-6}$	$\pm 1.5 \times 10^{-5}$
ANIK B	2300	N/A	N/A	N/A	$\pm 1 \times 10^{-5}$
ANIK C	2300	$\pm 5 \times 10^{-6}$	$\pm 1 \times 10^{-6}$	$\pm 1 \times 10^{-6}$	$\pm 1 \times 10^{-5}$
HERMES	2166.66	N/A	N/A	N/A	$\pm 1 \times 10^{-5}$

TABLE 2.4 - STABILITY OF SATELLITE LOCAL OSCILLATORS

2.5.2 Effects of Frequency Error

2.5.2.1 Adjacent Channel Interference (ACI)

When the wanted carrier and an adjacent unwanted carrier experience frequency errors such that partial overlap of their spectra (i.e., ACI) occurs, the unwanted carrier will impair the demodulation process for the wanted carrier in one or more of the following ways:

Higher Bit error rate
Intelligible or non-intelligible crosstalk
Demodulator capture
Increased demodulator C/N_o threshold
False muting circuit operation (for voice-activated systems)

A 12/14 GHz SCPC system is potentially more sensitive to ACI than a 4/6 GHz system as a result of: (i) larger absolute frequency errors (for a particular stability); (ii) larger variations (without power control) in carrier amplitudes due to fading. The problem is compounded when we consider multiple carrier levels without band separation.

The only component of frequency error that can cause spectral overlap is the unique frequency error described in Section 2.5.1, since frequency separation is maintained when all carriers experience common frequency error. However, if AFC is not used, common translation may result in detuning of the desired signal and introduction of an adjacent interfering signal at the demodulator input.

To avoid ACI, SCPC carriers are separated by guardbands, i.e., unoccupied frequency slots. If in a perfect system (no unique frequency error), an adjacent carrier separation of S is acceptable, then in a system with unique frequency error of up to ±Δf_t per carrier, a separation of $S + 2\Delta f_t$ is required.

Noting that typical signal bandwidths of SCPC carriers are 20-45 kHz, it is possible to define a bandwidth utilization efficiency factor E for a transponder;

$$E = \frac{\text{BW occupied by signals}}{\text{Total occupied BW}}$$

Table 2.5 shows E vs. Δf_t for systems employing 20 kHz and 45 kHz carriers.

Δf_t (kHz)	E (%)	
	20 kHz Ch.	45 kHz Ch.
0.1	99	99
1.0	91	96
10.0	50	69

TABLE 2.5 - SYSTEM BANDWIDTH EFFICIENCY VS. Δf_t

In a bandwidth-limited system every 1% of transponder bandwidth dedicated to guardbands represents at least $20,000 per year lost earning capability (based on a transponder lease of $2M/year). In a rural system where transponder channel capability is likely to be limited by power rather than bandwidth, the economic penalty for having guardbands will be significantly less.

2.5.2.2 CPSK Demodulator Pull-In Range

The pull-in range for a demodulator is defined for present purposes as the maximum input frequency offset that the demodulator can tolerate and still function properly. Ideally a demodulator should have a wide pull-in range; i.e., ± 5-10 kHz together with good steady state and transient performance. In practice a tradeoff must be made between pull-in range and such parameters as

(i) acquisition time,
(ii) demodulator losses.

Consider as an example, a second order high gain phase lock loop, operating in conjunction with an unmodulated carrier. From Gardner [23]:

$$\Delta \omega_p = 2\sqrt{\xi \omega_n K_v} \tag{3}$$

$$\text{i.e.,} \quad \Delta \omega_p \propto (\omega_n)^{1/2} \propto (B_L)^{1/2} \tag{4}$$

$$T_p = \frac{4.2 \ (\Delta f)^2}{B_L^{\ 3}} \ \text{sec.} \tag{5}$$

$$\sigma_\theta^{\ 2} = \frac{1}{2 \ \mathrm{CNR}_L} = \frac{N_o B_L}{2C} \tag{6}$$

$$\delta = \begin{cases} 10 \log \cos^2 (\sigma_\theta) \ \text{dB for 2-phase CPSK} \\ 10 \log \left(\dfrac{\cos^2 (\sigma_\theta)}{1 + \dfrac{E_b}{N_o} \sin^2 (\sigma_\theta)} \right) \text{dB for 4-phase CPSK} \end{cases} \tag{7}$$

where

$\Delta\omega_p$ = pull-in range (rad/sec)

ξ = loop damping ratio

ω_n = undamped natural frequency (rad/sec)

K_v = loop gain

B_L = single sided loop bandwidth

T_p = pull-in time

Δf = input frequency offset

σ_θ = rms phase jitter on VCO output signal

N_o = demod input noise power density

CNR_L = carrier to noise ratio within loop

C = input carrier power level

δ = effective demodulator E_b/N_o loss (in dB)

The implications of the above equations are as follows:

- To increase the pull-in range, the loop bandwidth must be increased (Equation 3).
- Increasing the loop bandwidth reduces the pull-in time (Equation 4) - a desirable situation in voice activated systems.

<u>but</u>

- Increasing the loop bandwidth increases the rms phase deviation (Equations 5 and 6) on the local carrier which gives rise to an effective energy per bit-to-noise density (E_b/N_o) loss δ.

Thus it is clear that optimum demodulator performance in terms of acquisition speed and efficiency is best served by designing a system with minimum frequency error.

2.5.3 Presently Used Techniques for Correcting Frequency Errors

2.5.3.1 General

The presently used techniques for minimizing frequency errors are:

(a) High stability sources.
(b) Periodic retuning.
(c) Automatic Frequency Control (AFC).

A combination of all three of these methods is used in present day operating systems such as Telesat's Thin Route System.

2.5.3.2 High Stability Sources

The most stable crystal oscillator available (e.g., HP 10544A) have aging rates of 5 x 10^{-10} per day which over 100 days yields 1 x 10^{7} or 1.4 kHz at 14 GHz. Thus even with this class of source, retuning is necessary once or twice a year.

The long term stability of rubidium or cesium standards is of the order of 10^{-10} to 10^{-11} indefinitely and therefore fully adequate without retuning for all ground station functions. However, for small terminals the cost of these devices may be prohibitive ~$10K each.

2.5.3.3 Periodic Retuning

Periodic retuning of oscillators is a practical but undesirable means of minimizing frequency errors. This method is deemed undesirable since regular service calls must be scheduled on an ongoing basis at a cost estimated between $100 - $1,000 per visit depending on location. In addition, there are technical difficulties associated with transporting and using the secondary standards with which comparison is made.

2.5.3.4 AFC

AFC, as presently performed in SCPC systems; e.g., SPADE, Thin Route, employs a pilot tone transmitted from a network reference station with an absolute error (Δf_p) not exceeding a few hundred Hz.

At each receiving earth station the pilot is frequency locked (see Figure 2.12) to a locally generated stable reference tone thereby removing all common frequency errors (i.e., Δf_{sat} and Δf_r)* from every message carrier but in the process introducing the additional insignificant error Δf_p to each carrier*.

2.5.4 Novel Techniques for Frequency Control

Here we consider some alternative approaches to frequency control, viz.:

(a) Dissemination of a network wide ultra stable frequency standard.

(b) Active control of satellite LO from ground.

(c) Ultra-high stability satellite oscillators.

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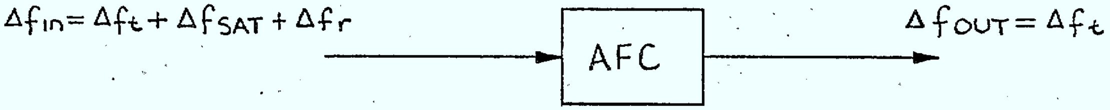
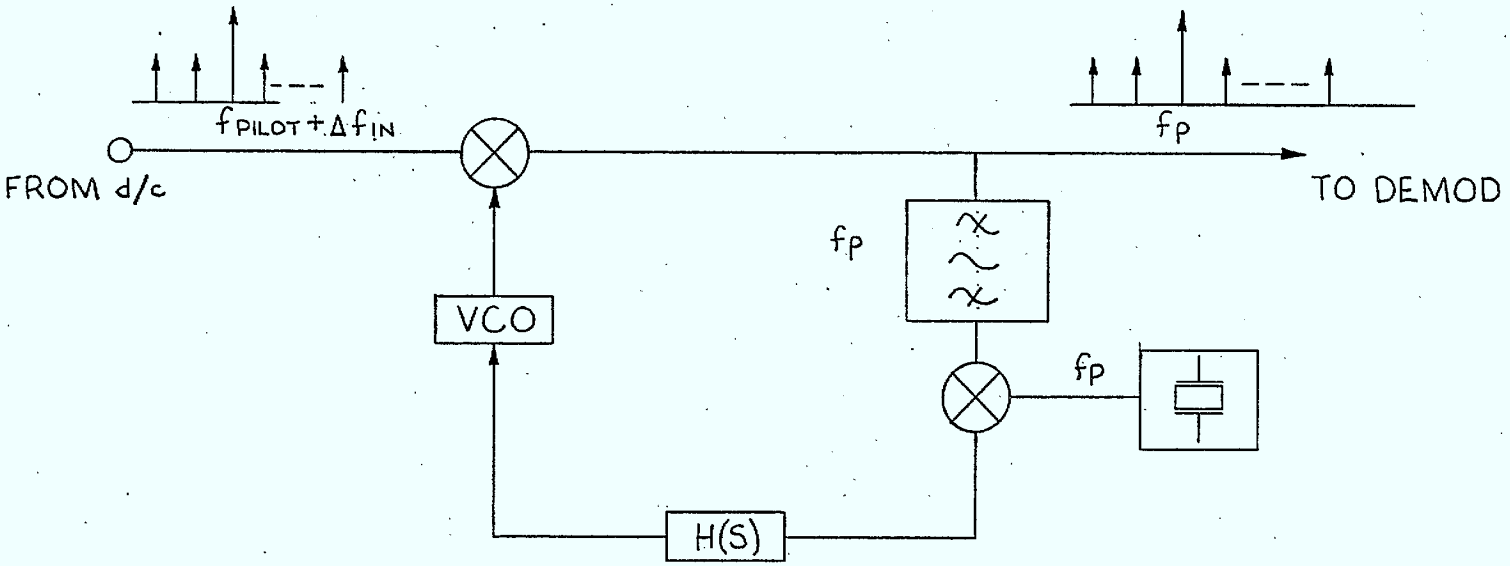
*In the case of a hubbed network in which the pilot originates from the gateway station, $\Delta f_t = \Delta f_p$ is also a common error at the multi-channel (Type B) rural terminal.



(a) REMOVAL OF COMMON FREQUENCY ERROR



(b) IMPLEMENTATION APPROACH

FIG 2.12 SIMPLIFIED AFC SYSTEM

2.5.4.1 Dissemination of a Network Frequency Standard

It is quite a simple task to disseminate an ultra-high stability (e.g., 10^{-10}) frequency standard to all earth stations in a network. This standard would then be used to synthesize all critical frequencies in the earth station. Using this approach, Δf_t and Δf_r could be reduced to a few Hz over indefinite periods thereby avoiding the need for retuning. Two possible means of achieving this are now discussed briefly:

(a) Two Tone Method

Here the reference station transmits two tones separated in frequency by a precisely known amount, e.g., 5.000 MHz. The tone pair retains its frequency difference while throughout the satellite link and is processed at the receive earth station using two narrowband receivers. After filtering, the two tones are mixed together (Figure 2.13) and the difference frequency is recovered to form the basis for further synthesis.

(b) Use of Data Clocks

If the SCPC system is digital the data rate (32 kbps/40 kbps etc.) can be used as a frequency reference. Each earth station as part of its receiving process recovers a data clock. Assuming the data clock originates at the network master station and is derived from an ultra stable source, then each earth station effectively becomes the recipient of this source.

This method is directly applicable for hub-remote network configurations. If the network is designed for free interconnectivity then the data clock bearing

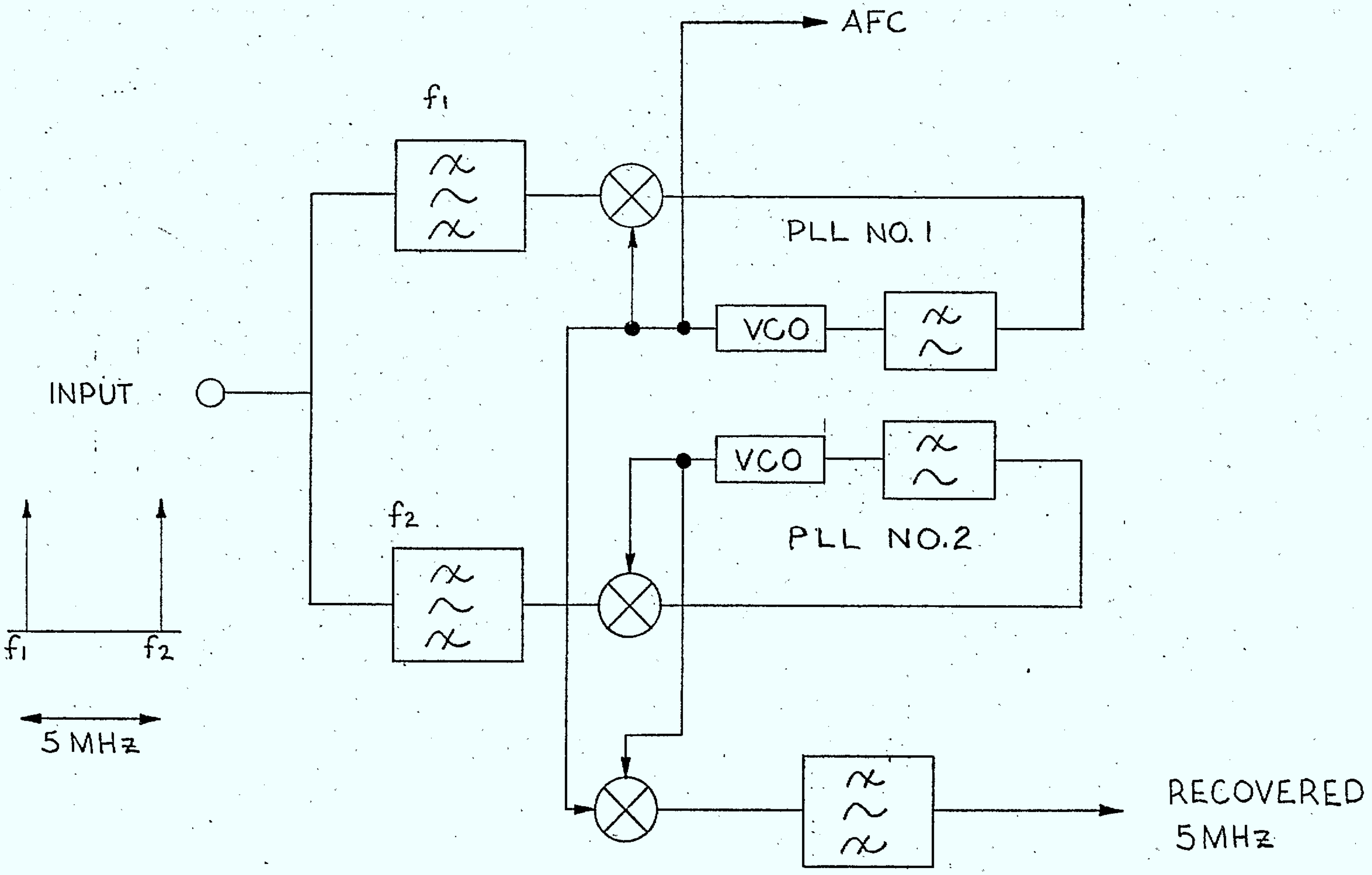


FIG. 2.13 TWO TONE METHOD—FREQUENCY RECOVERY

signal originating at the hub must be received by the remote stations in addition to the useful message traffic - i.e., the system approaches the two tone method described in (a).

2.5.4.2 Active Control of Satellite L.O. From Ground

With the network frequency standard disseminated as in Section 2.5.4.1, the outstanding problem becomes the stability of the satellite L.O. In future satellites designed for SCPC transmission, active control from the ground should attempt to control the L.O. frequency to within a few tens of Hz indefinitely.

In this approach the master station transmits a tone via the transponder and measures the frequency error by loopback. Commands are issued from the ground via the satellite command channel to modify the satellite LO frequency to null the error. The LO may be a VCO or a digitally programmable synthesizer with fine (e.g., 500 Hz) steps. The method selected should consider the effect of updating the LO frequency on the transponder traffic (i.e., phase modulation).

2.5.4.3 Ultra-Stable On-Board LO

A direct approach to achieving stable satellite LO performance is to employ an ultra-stable on-board standard either crystal or preferably atomic, from which the LO is derived.

Assuming a 2.5 GHz satellite LO, the long term frequency error exhibited might be as follows:

2.5.5 Phase Noise Effects

The preceeding discussion has not considered phase noise impressed on the carrier as an unwanted source of modulation. In the case of FM, phase noise > 300 Hz from the carrier is demodulated directly as baseband noise. With a coherent phase shift keyed signal, phase noise frequency components following outside the carrier recovery circuit loop bandwidth are not tracked and result in degradation in bit error rate vs E_b/N_o performance due to phase jitter [29] between the reference and the modulated carrier. Since their modulating signals are low frequency, SCPC systems are sensitive to phase noise. Furthermore there is a tradeoff in the design of a local oscillator to meet phase noise and long term stability specifications.

Wideband AFC techniques that employ a pilot to correct common frequency errors to the receiving earth station demodulator also serve to eliminate common phase noise components. A two tone difference or data clock disseminated frequency standard (see 2.5.4.1) must possess the necessary phase as well as long term stability characteristics for effective acquisition and demodulation. Note that in the case of CPSK or threshold extension FM the demodulator PLL loop bandwidth must be sufficiently large as to permit rapid acquisition of voice activated carrier, and hence can track low frequency phase noise. While both long and short term stability requirements must be considered, it is generally the former which is more stringent for unattended SCPC earth stations.

3.0 RURAL NETWORK CONFIGURATIONS

The purpose of this study is to provide the technical and cost factors necessary to assess whether a 12/14 GHz SCPC satellite system can serve some percentage of the rural population more cost-effectively than by other means. In order to derive the greatest benefit from satellite technology, its role should be complementary to planned and existing rural communications facilities. While our attention here is restricted to the satellite portion of an overall rural network, it is useful to consider briefly how a satellite communications facility could work together with subscriber radio systems and other facilities to effectively serve large rural areas. This is followed in this section by a functional description of three types of SCPC satellite terminals and the method(s) by which they access each other and the national switched network.

Figure 3-1 portrays the topology of a subscriber radio system with RF channel assignment from a Central Office station [24]. Due to the limited range of the subscriber radio equipment, it is necessary to install and maintain a large number of "autonomous" systems to cover a large rural area.

There may also be the additional requirement of providing interconnection between the Central stations and the public switched network. For rural communities possessing a small number of subscribers who could economically be interconnected by radio but who are beyond the range of the nearest national telephone exchange office, such interconnection might best be provided by a thin route satellite system.

The principle is demonstrated in Figure 3-1 which shows a satellite earth station collocated with the subscriber radio

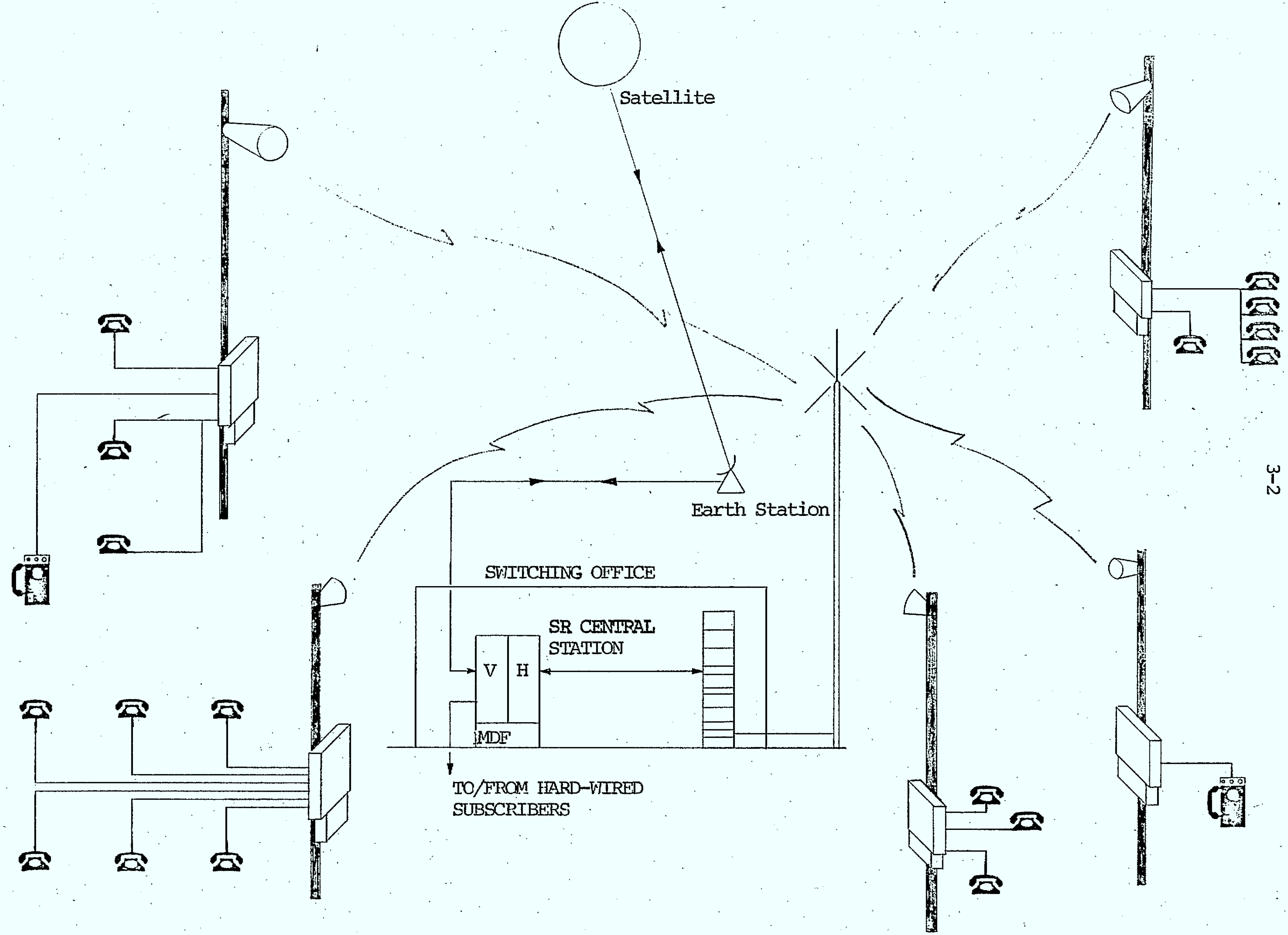


FIGURE 3-1 TYPICAL SUBSCRIBER RADIO (SR) SERVICE

central office. Such a multi-channel rural station would provide access to the national network for subscribers within a radius of say 20-25 miles. Note that calls between subscribers (i.e., neighbours) within the community are not routed through the satellite, but handled directly by the radio system. We might therefore expect to avoid a high percentage of those calls which would be double hopped through a hubbed system.

The local loops between one or more subscribers and the rural earth stations do not affect and are not included as part of the satellite system description. Cost-effective telephone service to a particular rural area, however, implies, an appropriate mix of satellite terminals, terrestrial radio equipment, aerial cable, and 4-wire pairs. With respect to the satellite portion of the system, the key question is"what is the optimum "coverage" area of a terminal of given capacity?" As it depends on the cost of (competing) terrestrial equipment, this distance could best be determined by the telephone companies given the satellite earth station cost information contained in this report. However, since some rural families will be separated by more than the maximum distance, single user (one channel) as well as multi-user (typically four channels) SCPC terminals are considered in this study.

3.1 Single-User, Multi-User and Gateway Earth Stations

There are basically three types of earth stations which need be considered for a rural SCPC network:

1) A single-user or Type A earth station that provides one network quality duplex voice circuit.

2) A multi-user or Type B earth station with at least a 4-circuit capacity.

3) A gateway station capable of terminating a large (up to several hundred) number of circuits.

A brief functional description of these stations follows.

Single-User or Type A Station

As the name suggests, this station is intended for providing telephone and/or data service to a single household which is typically located beyond an area which might be served by say a subscriber radio (SR) system. As mentioned in the introduction, this would be in areas lying beyond a 24 mile (40 Km) radius from the SR base station.

The Type A station would be located directly on the user's premises with the antenna erected outdoors and possibly the ground communications equipment (GCE) located indoors to obviate the need for a separate environmentally-controlled equipment shelter. To achieve this, the GCE might be configured in a highly integrated modular package which can be easily and unobtrusively installed. The GCE would be powered from the standard household 115 Volt A.C. main supply.

Some of the features of the station might be:

1) 2-meter antenna (see Appendix A).
2) Non-redundant equipment configuration.
3) Non-frequency-agile up- and down-converters.
4) Demand-assigned access to the rural network.
5) Voice-activation of the carrier.
6) Direct 4-wire interface to a standard telephone set.

Multi-User or Type B Station

The 4-channel Type B station is intended to provide dedicated circuits or interface to a small local exchange serving say 8 to 20 subscribers (depending on grade of service). In addition to providing access to/from the switched network, this exchange would perform the function of switching calls between subscribers.

In view of the 'community' aspect of the station, it would typically be collocated with the local switching office (No. 5 end office) which might also serve as the SR base station location for a subscriber radio system (refer to Figure 3-1). To reduce costs and also for security reasons, the GCE might be located within the switching office.

Operationally, the Type B station would be very similar to the Type A but might incorporate a limited amount of equipment redundancy to increase service availability. For cost reasons, modularity and large scale integration of communications subsystems would again be desirable. Non-frequency-agile operation, DAMA control and voice-activation of carriers would also be typical features of this station.

Gateway Station

The gateway station's function is basically to act as the focal point for all rural traffic to and from the switched network. There will typically be a single gateway station for the rural network in each spot beam. It would also serve as the control point for a centralized DAMA control and be responsible for the generation of the AFC system pilot. This station would clearly have multi-carrier transmission capability and, in view of its importance in the system, more elaborate (to block diagram level in the case of the rural stations) descriptions of the three types of stations are given in Section 4.2.

3.2 Method of Interconnection

This section addresses the method(s) by which rural stations access each other and the switched telephone network. The various transmission paths can be illustrated by means of Figure 3-2. Associated with each of the four spot beams is a 'rural exchange', each consisting of a gateway earth station and numerous rural stations (both Type A and Type B). As far as earth station interconnections are concerned, no distinctions between the single-user (Type A) and the multi-user (Type B) stations will be necessary.

Rural exchanges Nos. 1 and 2, located in the West and West Central spot beams respectively, can be used to illustrate the various interconnections.

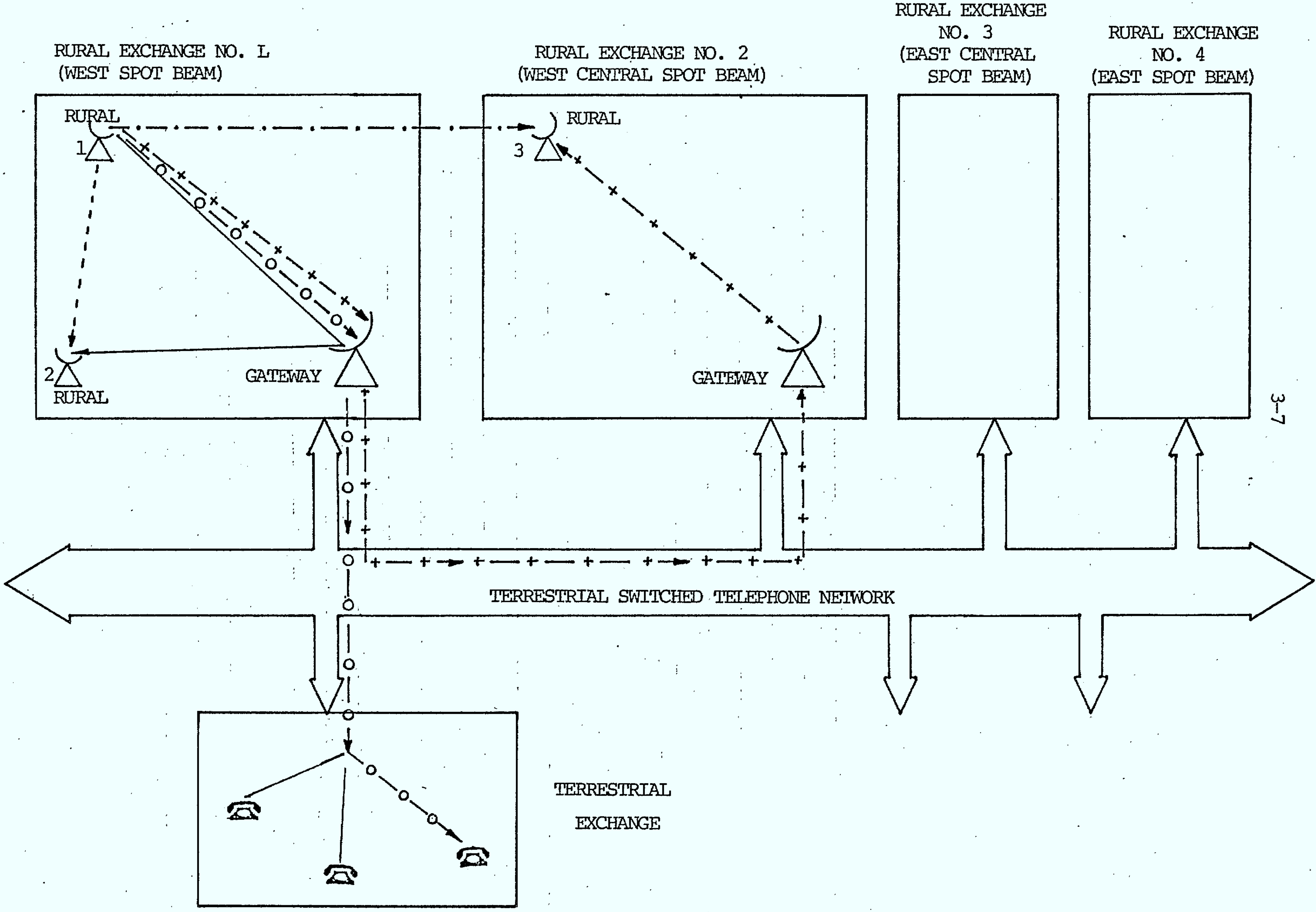
For rural-to-rural interconnections (e.g., terminal 1 to terminal 2) within a spot beam, there are two possible transmission paths:

1) Double hop through the gateway station, i.e., a hubbed system.
2) Single hop, i.e., a fully connected system.

The advantages and disadvantages of hubbed and fully connected systems have previously been discussed in Section 2.0.

For rural exchange-to-terrestrial network connections (e.g., from terminal 1), only a single satellite hop to the gateway station will be required. However, it will be necessary to ensure that rural trunk circuits are routed strictly via the terrestrial microwave system of the switched network to avoid tandem satellite connections, e.g., via heavy route satellite message carriers.

FIGURE 3-2 - RURAL NETWORK INTERCONNECTION



For rural-to-rural connections between spot beams (e.g., terminal 1 to terminal 3), there are two possibilities:

1) Single hop, direct interconnection.
2) Double hop interconnection via the West gateway station, the terrestrial switched network (see comment above for rural-to-terrestrial exchange connections) and the West Central gateway station.

Single hop, direct interconnection implies the following:

1) A fully-connected national rural network.
2) A common DAMA system for all four spot beams.
3) Multi-transponder frequency agility.
4) Dual polarization transmit capability in the rural earth stations.

In view of the increased cost impact of points 3 and 4 on the rural earth stations alone, such a system is not recommended. It is also very unlikely that the requirement for such connections will be significant enough to justify the cost and complexity of such a network.

The implementation of echo suppression in the rural network has not been addressed in this study but is of paramount importance in satellite systems. This subject has received extensive treatment in the literature and also in an MCS study for the Trans Canada Telephone System [25]. Present TCTS application rules require that all satellite trunks be equipped with split echo suppressors. With the emergence of the digital toll network both in Canada and the U.S.A., there are numerous network and cost factors which have to be considered in the implementation of echo suppression [26].

Suffice it to say that some form of echo suppression, whether it be by analog or digital echo suppressors or echo cancellers, will be required. For the Type A single-user stations, an echo suppressor is not required if four-wire connection to the subscriber telephone(s) is employed; alternatively, the echo suppression function can easily be incorporated into the channel unit (see Section 2.4). For the Type B multi-user terminal, it may or may not be more cost-effective to utilize conventional echo suppressors located in the local No. 5 end office.

For rural-to-rural connections, whether single or double hopped, echo suppression will be performed at the rural terminals (or possibly in the collocated end office for Type B stations). It will be necessary to ensure that no more than two split echo suppressors are present in any circuit connection.

For rural-to-terrestrial exchange connections, echo suppression will normally be performed at the rural terminal and in the No. 4 toll office at the end of the toll trunk.

3.3 Network Growth and Development Strategies

A demand-assigned SCPC network, either fully connected or hubbed, has been hypothesized as a means of extending telephone service in rural areas. The projected rate of growth of the system as well as its final configuration will influence the baseline design. Larger networks favour the use of automated control and supervision, and possibly the exploitation of new technology. A pre-assigned mode of operation may be favoured until the total number of operative channel units in the system exceeds the number of available satellite channels.

A hubbed system using a pre-assigned circuit arrangement has the following important features:

1) Easily accommodates signalling, switching and billing currently employed in the DDD network.*

2) Complete interconnectivity between stations achieved through double hopping.

3) New rural terminals can be added with a minimum of equipment sophistication (i.e., no DAMA equipment).

4) No modification required in the rural stations or the gateway station (except for possibly increasing the number of channel units) as new rural terminals are added.

Pre-assigned operation would normally be considered at start of service if the minimum leasable or available transponder bandwidth far exceeded the requirement (with DAMA present). However, as discussed in 2.3.3.1, for the low-channel unit

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*One of the main difficulties with DAMA is the need to provide an interface that ensures compatibility of the terrestrial and satellite portions of an end-to-end dial-up circuit.

usage factors expected, the overwhelming bandwidth advantage of DAMA probably dictates its use from the outset. Such is not necessarily the case with power, however, and the following techniques might be considered to upgrade capacity (# of simultaneous circuits permitted over the satellite) of the system:

1) Introduce voice activation of carriers.
2) Increase the G/T values of the rural earth station and/or the gateway station.
3) Introduce up-link power control.
4) Introduce more efficient SCPC modulation techniques.
5) Expand the space segment leased to support the service.

These techniques can be instituted with varying degrees of ease and cost. The way in which service grows and the rate of growth will both have a major impact on implementation strategies.

4.0 EARTH STATION REQUIREMENTS AND CONCEPTUAL DESIGN

In this section, link calculations to determine the EIRP and high power amplifier (HPA) requirements for the 2-meter Type A single-user earth terminal are presented for both homogeneous and non-homogeneous (2-carrier level) systems. Based on these results, HPA requirements for three candidate 4-channel (Type B station) HPA configurations are derived in Appendix C.

Two modulation techniques (for comparisons, see Section 2.2) have been considered:

1) 32 kbps Δ-mod/4Ø CPSK/SCPC
2) FM/SCPC - with and without threshold extension demodulation (TED)

Voice-activation of carriers and Anik C (primary coverage) operation are also assumed and the effect of up-link power control in a 2-carrier level system investigated.

These results permit some recommendations to be made on the transmission parameters for a rural SCPC system. Emphasis is placed on establishing tradeoffs; hard choices are only made when clearly justified economically.

Results of the analysis are reflected in the conceptual designs of the Type A and Type B rural earth stations presented as a conclusion to this section. Some preliminary evaluation of earth station reliability together with rough cost estimates for the stations are included and serve as key indicators of overall economic viability. Discussion of the gateway earth station will be limited to assumptions made on its size and G/T for link calculation purposes and its function within the rural SCPC network for the transmission system chosen*.

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*A gateway station would probably also originate TV and trunk message. The incremental cost to fit it with SCPC equipment and hence its impact on the economic viability of a full scale rural SCPC system would, therefore, be relatively small.

4.1 Link Budgets

To determine transmit EIRP and HPA requirements for the rural earth stations, link calculations have been performed for both a homogeneous (fully connected) and a 2-carrier level (hubbed) SCPC system.

Transponder SCPC capacities for homogeneous and 2-carrier level FM and Δ/PSK systems are derived. The effect of implementing up-link power control at the gateway station only (see Section 2.3.4) on transponder capacity for the 2-carrier level (hubbed) SCPC system is also indicated.

Anik C and other link parameters are listed in Table 4.1. Assumptions utilized for the link calculations are stated in Table 4.2 and the required unfaded carrier-to-noise density ratios (C/N_o's) for digital and analog transmissions [1] are summarized in Table 4.3.

4.1.1 Homogeneous System

The results of the link calculations for a homogeneous SCPC system are summarized in Table 4.4.

System	Required Unfaded C/N_o	Approx. Transponder Capacity (VOX Factor = 2.5)	Required Earth Station EIRP	Required Earth Station HPA
32 kbps Δ-mod	58.9 dB-Hz	690	47.9 dBW	3.2 Watts
FM	59.8 dB-Hz	560	48.8 dBW	1.9 Watts
FM-TED	58.1 dB-Hz	830	47.1 dBW	1.3 Watts

TABLE 4.4 - HOMOGENEOUS (2-METER) SCPC SYSTEM:LINK CALCULATION RESULTS

ANIK C SATELLITE	Single Carrier Saturation Flux Density	-80 dBW/m^2
	Satellite Receive G/T	+1 dB/°K
	EIRP (Primary Zone)	48 dBW
	Transponder Bandwidth	54 MHz
Up-Link Free-Space Loss @ 14.25 GHz and 10° Elevation		207.8 dB
Down-Link Free-Space Loss @ 12.0 GHz and 10° Elevation		206.2 dB
Gain of a 1-m^2 Antenna @ 14.25 GHz		44.5 dB
10 log k (k $\triangleq$ Boltzmann's Constant)		-228.6 dBW/°K-Hz

TABLE 4.1 - LINK PARAMETERS

1.	Type A Single-User Earth Station G/T (2-m Antenna + 340°K LNA)	19.3 dB/°K
2.	Gateway Earth Station G/T (4.57-m Antenna + 340°K LNA)	26.5 dB/°K
3.	Antenna Efficiency	55%
4.	Gain Calculations at Mid-Band Frequencies:	
	Transmit	14.25 GHz
	Receive	12.0 GHz
5.	Multi-Carrier Satellite Input Backoff	11 dB
6.	Centre Channel Carrier-to-Intermodulation Noise for Equal and Equally Spaced Carriers @ IBO = 11 dB	15 dB
7.	Transponder Usable Bandwidth	54 MHz
8.	SCPC Channel Spacing	22.5 kHz
9.	Earth Station Transmit Waveguide Loss	1 dB
10.	Single Carrier HPA Output Backoff (see Appendic C):	
	PSK	3 dB
	FM	0 dB
11.	Voice-Activation Factor	2.5 (4 dB)
12.	Up-Link Power Control Factor (Average)	4 dB

TABLE 4.2 - LINK CALCULATION ASSUMPTIONS

System	Threshold	Fade Margin to Threshold	Modem Implementation Margin	Subjectively Equivalent Performance at Threshold	Required Unfaded C/N_o
32 kbps Δ-mod	BER = 10^{-2}	7 dB	2.5 dB	14,000 pWpO	58.9 dB-Hz
FM	C/N = 10 dB	7 dB	1 dB	10,000 pWpO	59.8 dB-Hz
FM With TED	C/N = 7.5 dB	7 dB	1 dB	10,000 pWpO	58.1 dB-Hz

TABLE 4.3 - REQUIRED UNFADED CARRIER-TO-NOISE DENSITY RATIOS

The above results indicate that a homogeneous SCPC system of 2-meter earth stations (G/T ≅ 19.3 dB/°K) would be very power limited* (bandwidth limit = 2400 channels) for the assumed operating conditions.

Earth station HPA requirements for all three cases could be satisfied with a 10 Watt travelling-wave tube amplifier (TWTA) operating at the appropriate output backoff.

4.1.2 2-Carrier Level System

For a 2-carrier level, hubbed (2-m ↔ 4.57-m) SCPC system, the larger G/T at the gateway station permits the EIRP from the rural stations to be reduced. This results in two advantages, relative to a system of equal carriers (homogeneous system), namely:

1) Transponder power is utilized more efficiently (and hence channel capacity is increased) when a significant proportion of the satellite circuits are terminated rather than just switched (double hopped) at the gateway. Introducing selectable (call dependent) transmit carrier levels in a fully connected system achieves the same end, but complicates the design of the rural station.

2) EIRP requirements at the rural earth stations are reduced.

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*For power limited systems in which excess bandwidth allows the selection of a frequency plan which minimizes the effects of IM product noise, the backoff that maximizes transponder capacity can be considerably lower (say 7 dB) than the 11 dB value assumed in Table 4.2. Reducing the 11 dB backoff to the optimum also increases (but not quite on a 1:1 basis) the EIRP per carrier. Since the total cost of HPA's is expected to be more significant than space segment costs with DAMA, low duty factor users, such a reduction is not justified. On the other hand, increasing the input backoff beyond the point at which intermodulation noise is a significant contributor in the link equation rapidly reduces transponder capacity without altering required EIRP per carrier. 11 dB is therefore considered about optimum for both the homogeneous and hubbed configurations.

The penalty of adopting this approach is, of course, that rural-to-rural calls must be double hopped, implying less efficient use of satellite bandwidth, and the gateway must be fitted for additional SCPC channel capacity to accommodate its role of double hopping satellite circuits as well as providing access to the switched network.

The results of link calculation (Table 4.5) attest to the aforementioned advantages of the 2-carrier level system.

System	Required Unfaded C/N_o	Approx. Transponder Capacity (VOX Factor = 2.5)	Required Rural Earth Station EIRP	Required Rural Earth Station HPA
32 kbps Δ-mod	58.9 dB-Hz	1094	43.0 dBW	1.0 Watt
FM	59.8 dB-Hz	890	43.9 dBW	0.6 Watt
FM-TED	58.1 dB-Hz	1320	42.1 dBW	0.4 Watt

TABLE 4.5 - 2-CARRIER LEVEL SCPC SYSTEM:LINK CALCULATION RESULTS

Comparing the results in Tables 4.4 and 4.5, we note the following for the 2-carrier level system:

1) Transponder capacity for rural-to-gateway circuits has been increased by nearly 59% (note, however, that this system is still power limited).

2) EIRP from the rural station has been reduced by almost 5 dB.

3) HPA power capacity required has been decreased to a power level attainable by solid state power amplifiers.

The advantages which accrue from the above (as compared to a homogeneous system) are:

(a) Reduced space segment charge per circuit providing double hop (rural-to-rural) calls comprise less than 75% of the total.

(b) Reduced off-axis interference transmitted from the rural earth station.

(c) The opportunity of using solid state power amplifiers instead of TWTA's. The potential advantages of solid state HPA's are many:

- higher reliability and extended life
- higher efficiency
- smaller size and weight
- lower cost due to solid state manufacturing techniques
- better linearity performance
- low power supply voltages

If up-link power control is added to the larger carriers (gateway → rural links), which contribute approximately 75% of the total up-link power, the saving in transponder power can be used to further increase transponder channel capacity. This can be illustrated as follows: for the 2-carrier level system, a large carrier-to-small carrier ratio of 4.67 dB ($\beta = 2.93$) has been determined in the link calculations. The percentage of the total up-link power contributed by the larger carriers is therefore:

$$\frac{\beta}{1 + \beta} \times 100\% \quad = \quad 74.56\%$$

If an average (under dynamic conditions) up-link power control advantage of 4 dB (2.51) is assumed for the larger carriers, the total up-link power required to support a given number of circuits with the same link availability is therefore reduced to

$$\frac{1 + \frac{\beta}{2.51}}{1 + \beta} \times 100\% = 55\%$$

The (power limited) transponder capacity can thus be increased by a factor 1.81 without altering the design or operational complexity of the rural stations (see Section 2.3.4). Results are summarized in Table 4.6.

System	Approx. Transponder Capacity (VOX Factor = 2.5, Up-Link Power Control Factor = 4 dB)
32 kbps Δ-mod	1980
FM	1610
FM-TED	2390

TABLE 4.6 - 2-CARRIER LEVEL SYSTEM TRANSPONDER CAPACITY WITH VOICE-ACTIVATION AND UP-LINK POWER CONTROL

4.1.3 Conclusions

It is clear that a 2-carrier level, hubbed system offers significant transmission advantages in terms of reduced interference to adjacent satellites and the use of a more economical and reliable solid state power amplifier at the rural station. The implementation of up-link power control on gateway-to-rural station links is also a desirable feature which should be considered as a means of reducing space segment circuit charges without affecting the cost of the rural station.

4.2 Earth Station Description

Two performance parameters have serious impact on the cost of an SCPC earth station, namely

(1) circuit noise
(2) circuit availability

Since they determine fair weather C/N_o (see Figure 2-1) and fade margin requirements (see Appendix B) respectively, both the above enter into link equations to size the earth station. Circuit availability depends not only on fade margin, however, but also on the reliability and maintenance of earth station equipment. An earth station availability requirement influences both capital and operating costs for the station, and should be considered as part of the earth station description. A parametric approach to availability is taken in this section since an objective for the service has not been specified.

Circuit availability can be defined as the percentage of time a given duplex circuit between two stations is available. Unavailability due to adverse propagation and no assignable DAMA channels are not addressed.

The availability of earth station equipment supporting a given duplex circuit can be broken down (assuming non-dependent failures) into a product of subsystem availabilities:

$$A = \prod_{k=1}^{N} A_k$$

where

$$A_k = \frac{MTBF_k}{MTBF_k + MTTR_k}$$

$MTBF_k$ = mean time between failures of k'th subsystem

$MTTR_k$ = mean time to repair of k'th subsystem

When redundantly configured subsystems are employed, it is necessary to relate net availability A_k to unit availability $\hat{A}_k$. Assuming a maintenance policy which responds to system failures and a fixed MTTR [27], the following formula can be applied:

$$A_k = 2\hat{A}_k - \hat{A}_k^2$$

Factors that affect MTTR are maintainability, accessibility, test facilities, spares provisioning, maintenance philosophy, etc. A comprehensive discussion of the various factors to be considered in a Thin Route SCPC system is contained in [1].

In the ensuing sub-sections, the MTTR is assumed to be the same for all subsystems and availability is determined for a range of MTTR's.

For the Type A single-user rural earth station, a basic non-redundant equipment configuration is assumed. For the Type B earth station, a number of different configurations are considered. In all cases, the subsystem MTBF's assumed are based on best estimates of comparable 4/6 GHz equipment. Since 4/6 GHz technology is, however, well developed or 'mature', the results obtained for 12/14 GHz technology may at present be slightly optimistic.

In the area of costing, again only 'best estimates' can be applied in view of the lack of any real cost data for 12/14 GHz equipment. Estimates of capital cost for quantity 10 of the various subsystems have been made and a 15% cost discount applied for large quantities (i.e., quantity 100).

Assumptions which either directly or indirectly affect earth station costs are listed in Table 4.7.

4.2.1 Type A Single-User

The typical configuration of a Type A rural earth station is illustrated in Figure 4-1 and its basic characteristics listed in Table 4.8. The station is assumed to operate within a 2-carrier level, hubbed SCPC system and accesses the gateway earth station on a demand-assignment basis.

The station consists of:

1) A 2-meter Antenna
2) An Outdoor Unit
3) An Indoor Unit

The outdoor unit is weather-sealed and mounted immediately behind the antenna dish and in close proximity to the feed-horn assembly to minimize RF losses.

Interfacility links (IFL) connect the Outdoor Unit to the Indoor Unit at an IF frequency of 200 MHz (traffic paths). IFL links for power distribution, remote sensing and reference frequency feeds for the up-converter and down-converter are also provided.

Locating the Indoor Unit inside the user's residence obviates the need for and added expense of providing a separate equipment shelter equipped with environmental controls.

1. Capital costs are based on a prime contractor purchasing basis, i.e., subsystems are commercially available. Development costs are not included in the costing of the earth stations.

2. The costs of the land and site preparation are not included. This is reasonable if earth stations are located on customer premises, e.g., individual's home or Telco property.

3. The cost of building facilities is not included.

4. Connection to commercial prime power is available at no additional capital costs.

5. The cost of operation and maintenance is not included.

6. The costs of providing spares and test equipments are not included.

7. Import duty, currency exchange, broker's fee, freight costs and sales taxes are not included.

TABLE 4.7 - COST-RELATED ASSUMPTIONS

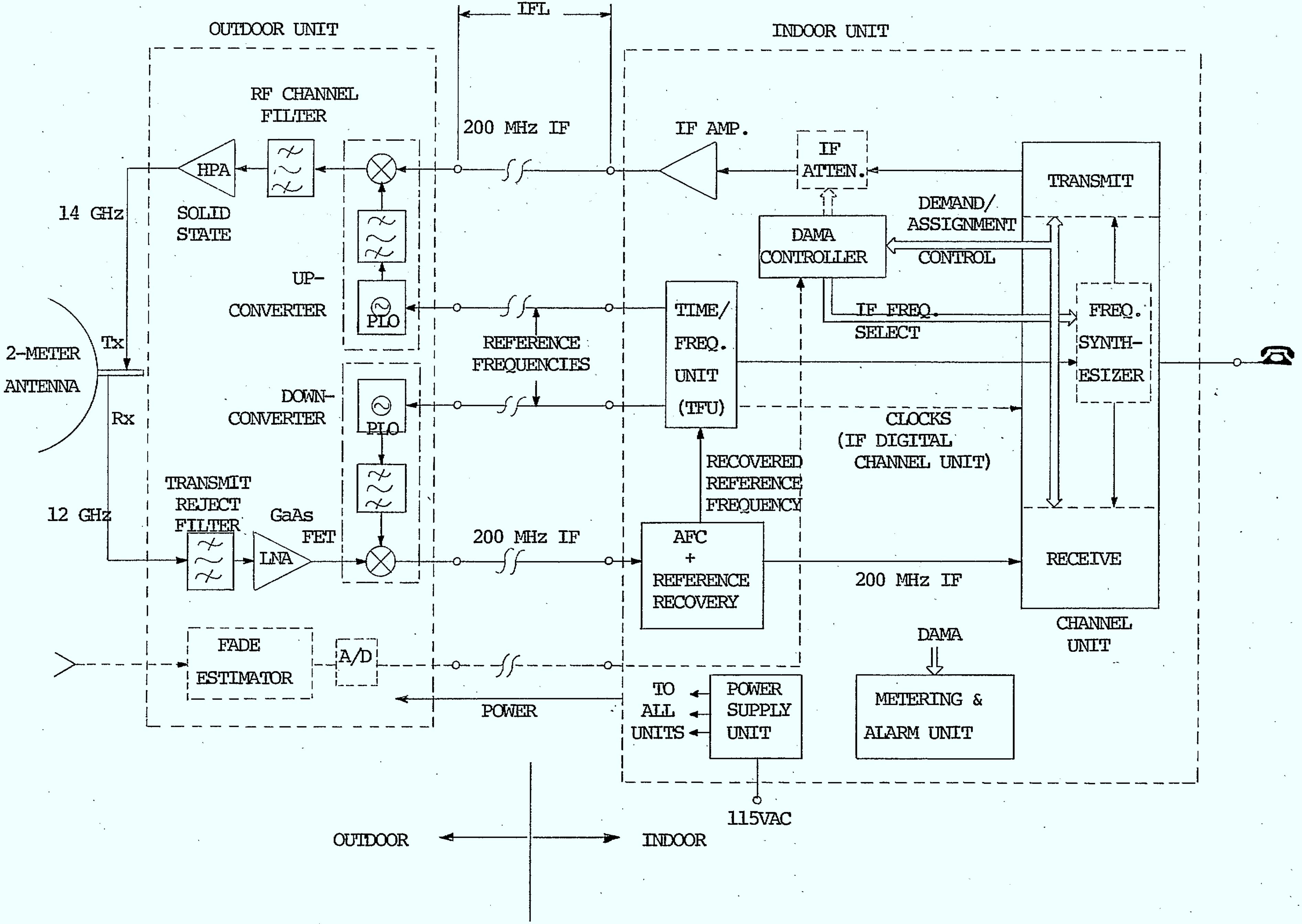

FIGURE 4-1 - TYPE A SINGLE-USER EARTH STATION CONFIGURATION

Antenna Size	2-meters
Station G/T	~ 19.3 dB/°K
Low Noise Amplifier (LNA)	~ 340°K GaAs FET
High Power Amplifier (HPA)	~ 1 Watt solid-state
Transmission Capability	1 SCPC Carrier (FM or 32 kbps Δ-mod)
Frequency Agility	Non-Agile
Access Technique	Demand-Assignment Multiple Access (DAMA)
Equipment Configuration	Non-redundant

TABLE 4.8 - TYPE A RURAL EARTH STATION CHARACTERISTICS

4.2.1.1 Outdoor Unit

The Outdoor Unit is comprised of:

1) Up-converter (mixer, harmonic filter, 14 GHz Phase-Locked Oscillator (P.L.O.))
2) Down-converter (mixer, harmonic filter, 12 GHz P.L.O.)
3) RF Channel Filter
4) 1 Watt solid-state HPA
5) Transmit Rejection Filter
6) 340°K GaAs FET LNA

Up-/Down-Converter

To minimize RF costs and alignment, a single stage up-conversion/down-conversion process is postulated. This requires that the IF frequency be as high as possible since the RF channel filter will be centered on the sum of the local oscillator (L.O.) and IF frequencies. The critical rejection which the channel filter must therefore provide is the rejection of the L.O. frequency. Since the RF mixer typically provides 30 dB of isolation (L.O. to RF), it is required that the channel filter provide a further 30-40 dB of L.O. rejection. For a 200 MHz IF, a 0.5 - 1% bandwidth waveguide filter should be capable of providing this rejection at an offset frequency of Δf = 200 MHz.

Failing this, however, the more conventional and expensive method of double up-/down-conversion would have to be adopted.

The reference frequencies for the P.L.O.'s are generated in the TFU (Time/Frequency Unit) located in the Indoor Unit to minimize frequency variations with temperature fluctuation.

HPA

After up-conversion to the 14.0 - 14.5 GHz transmit frequency band, the outgoing signal is amplified by the HPA and transmitted to the satellite. It was earlier determined that, for the EIRP required in a 2-carrier level SCPC system, a solid-state HPA would suffice and is clearly more desirable than a TWTA because of its lower cost, size, weight, higher reliability, etc. In addition, its size, weight and low power requirement greatly facilitates its integration into the Outdoor Unit.

The two most promising solid-state devices are the GaAs FET power amplifier, a 5-Watt version of which is expected to be available within the next year or two, and the IMPATT diode amplifier. 10-Watt versions of the latter are being forecasted.

LNA

On the receive side, a transmit rejection filter is used to attenuate the cross-coupled transmit band by typically 60 dB. The signal received from the satellite in the 11.7 - 12.2 GHz band is amplified in the low-noise amplifier (LNA) and then down-converted to a 200 MHz IF.

There are basically only two types of low noise amplifiers which are of interest at 12 GHz: the parametric amplifier ($T_{LNA} \cong 90°K$ to $120°K$) and the uncooled solid-state GaAs FET LNA ($T_{LNA} \cong 340°K$).*

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*In Canada, a prototype Peltier-cooled GaAs FET at 170°K is expected to be made available within the next year. A 290° GaAs FET LNA (uncooled) is also being forecasted in the industry.

On the basis of cost, reliability, size, weight and power consumption, the solid-state GaAs FET LNA is the clear choice.

4.2.1.2 Indoor Unit

The Indoor Unit is comprised of:

1) A channel unit
2) DAMA controller
3) 200 MHz IF equipment
4) Time/Frequency Unit (TFU)
5) Metering and Alarm Unit
6) Power Supply Unit

A brief description of the main sub-units follows.

Channel Unit

The channel unit (either digital or FM - see Section 2.4) contains a single frequency synthesizer for the generation of both transmit and receive IF frequencies which are mirror images in frequency with respect to the AFC system pilot, i.e., frequency pairing is assumed. Frequency selection is determined by the DAMA controller. The signal interfaces to the channel unit are at an IF frequency of 200 MHz and voice frequency (VF) at baseband.

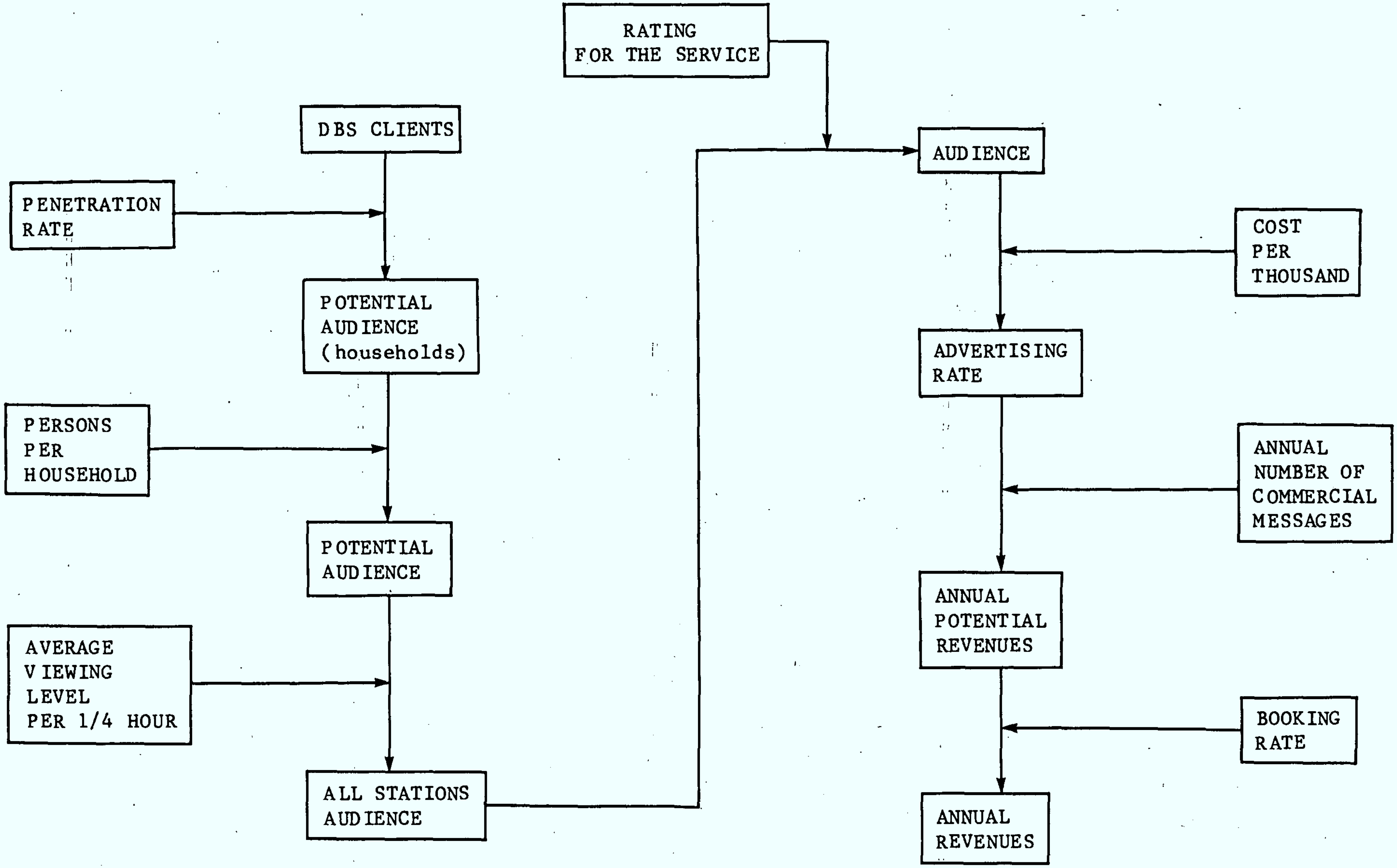
Since the channel unit also serves as the demand-assignment channel unit, signal interfaces from the channel unit to the DAMA controller are provided.

DAMA Controller

The basic functions of the DAMA Controller are:

Figure 5-2

ADVERTISER SUPPORTED SERVICES: METHODOLOGY



1) To handle the demand-assignment control messages to and from the central DAMA Controller.

2) To select the proper pair of transmit/receive IF frequencies for the modem in the channel unit in response to directives from the central DAMA controller.

3) To generate various supervisory and call-progress tones.

In the idle mode (phone on-hook), the DAMA controller selects a frequency pair corresponding to the demand-assignment control channel (DACC) and continuously monitors the DACC for incoming messages from the central DAMA controller.

Other functions which might be performed by the DAMA controller include:

1) In-station diagnostic routines with faults reported to a central maintenance depot and/or indicated on the Metering and Alarm Unit. These routines might be executed either on a regular basis or on commands from the central DAMA controller with system status reports forwarded to the maintenance depot (possibly collocated with the gateway station) at off-peak hours.

2) In a fully-connected, homogeneous SCPC system, the DAMA controller might be required to perform up-link power control (by varying an IF attenuator) in response to either fade information supplied by the distant station's DAMA controller and/or the local fade estimator* (see Figure 4-1).

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*This could simply be a suitably calibrated rain gauge.

AFC + Reference Recovery Unit

This unit performs the following functions:

1) Spectrum centering (AFC) of the received SCPC spectrum by means of a system pilot generated from the gateway station (see Section 2.5).

2) Recovers the ultra-stable reference frequency generated from the gateway station by using the system pilot in conjunction with a second system pilot (see Section 2.5).

The spectrum-centered IF signal is routed to the receive IF port of the channel unit for processing. The recovered ultra-stable reference frequency is routed to the TFU.

Time/Frequency Unit (TFU)

The function of the TFU is to use the recovered reference frequency to provide the following:

1) Higher reference frequencies for the phase-locked oscillators in the Outdoor Unit.

2) A reference frequency for the channel unit frequency synthesizer.

3) Various clock signals for the channel unit (if digital).

To enable initial acquisition of the ultra-stable reference frequency, a separate VCXO with a frequency stability of say 1×10^{-6} might be provided for the down-converter P.L.O. and might be arranged to be automatically switched in upon loss of the recovered stable reference frequency.

4.2.1.3 Reliability Analysis

For the basic non-redundant equipment configuration assumed for the Type A station, the reliability model simply consists of all subsystems connected in series (Figure 4-2). The reliabilities of the Metering and Alarm Unit and household environmental systems are not included since, in general, failures of these 'secondary' subsystems will not affect traffic. Prime power availability has not been included mainly because of its present unpredictability.

The MTBF's assumed for the various subsystems and the subsystem availabilities for an MTTR = 40 hours are tabulated in Table 4.9. Earth station availability,

$$A_{ES} = \prod_{i=1}^{13} A_i$$

as a function of MTTR is given by Figure 4-3.

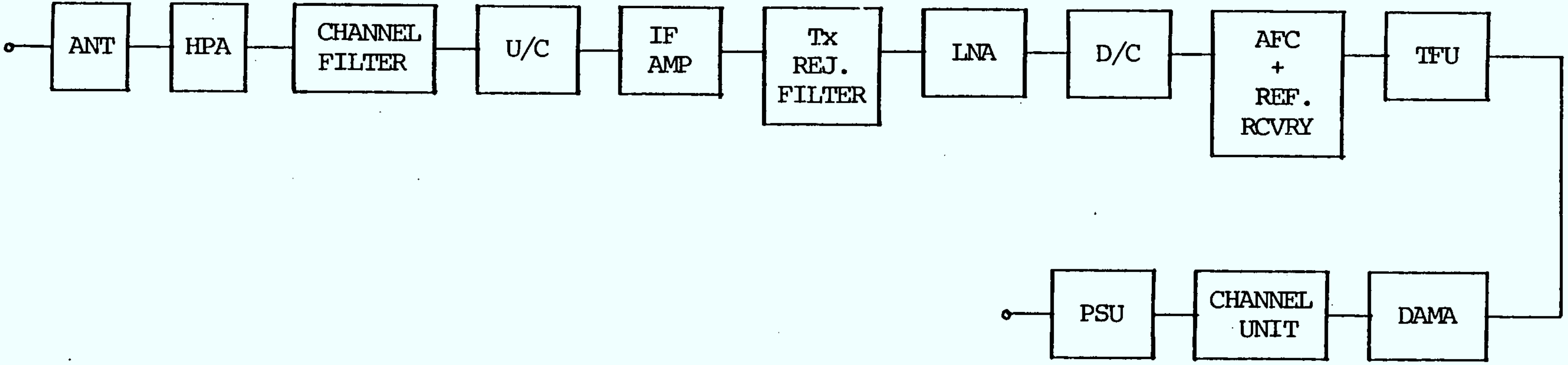
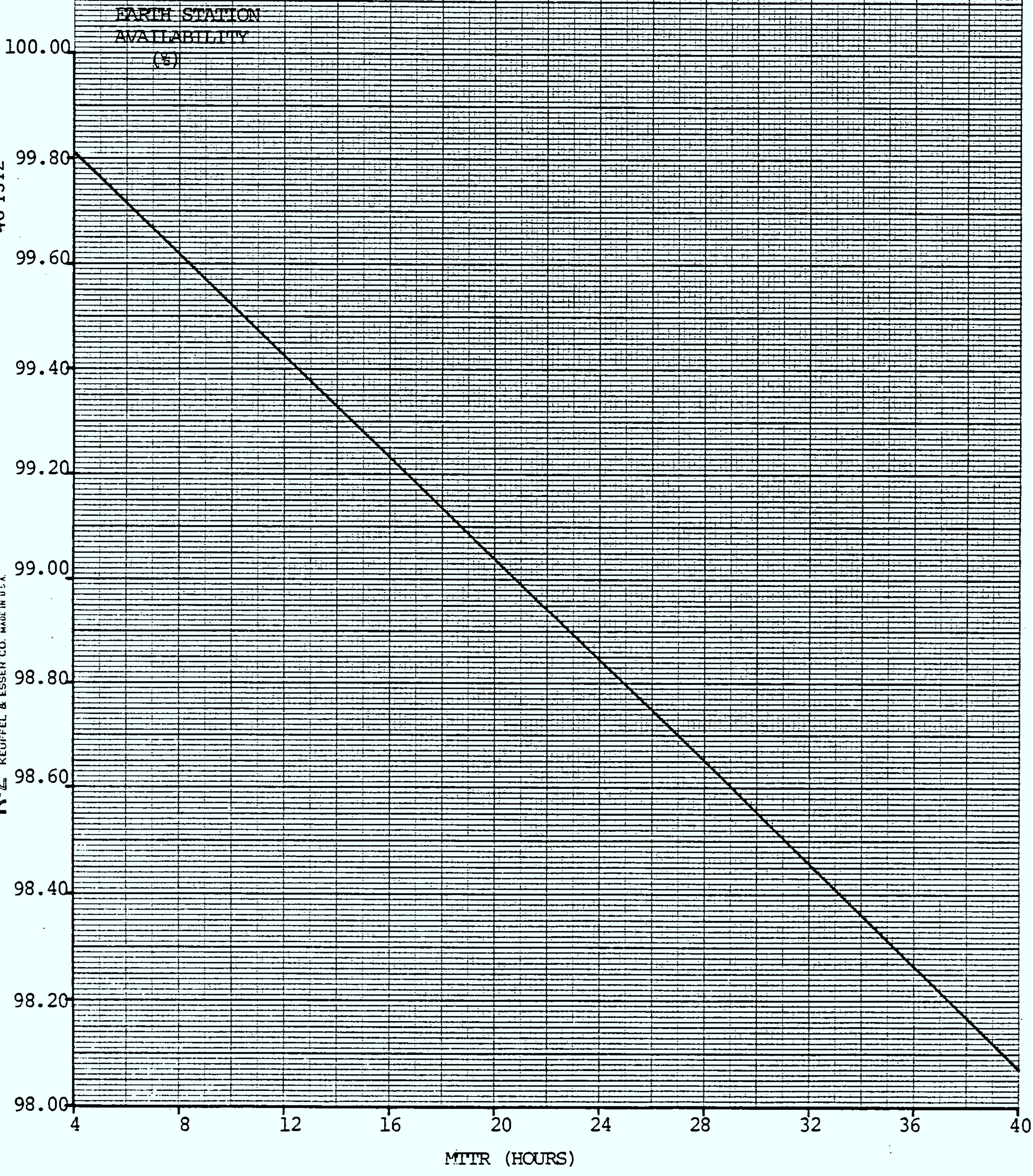


FIGURE 4-2 - RELIABILITY MODEL - TYPE A RURAL EARTH STATION

	SUBSYSTEM	ESTIMATED MTBF (Hours)	AVAILABILITY	
			MTTR = 4 Hrs.	MTTR = 40 Hrs.
1.	Antenna	500,000	0.99999	0.99992
2.	Solid-State HPA	66,700	0.99994	0.99940
3.	GaAs FET LNA	66,700	0.99994	0.99940
4.	Up-Converter (Non-Agile; Single Stage Conversion)	11,600	0.99966	0.99656
5.	Down-Converter (Non-Agile; Single Stage Conversion)	11,600	0.99966	0.99656
6.	RF Channel Filter	500,000	0.99999	0.99992
7.	Tx Reject Filter	500,000	0.99999	0.99992
8.	Tx IF Amp.	33,000	0.99988	0.99879
9.	AFC + Reference Recovery	14,600	0.99973	0.99727
10.	Time/Frequency Unit (TFU)	34,400	0.99988	0.99884
11.	DAMA Controller	33,000	0.99988	0.99879
12.	Channel Unit	16,600	0.99976	0.99760
13.	Power Supply Unit	16,600	0.99976	0.99760

TABLE 4.9 - SUBSYSTEM RELIABILITY DATA

FIGURE 4-3 - TYPE A SINGLE-USER EARTH STATION CIRCUIT AVAILABILITY VS. MTTR



4.2.1.4 Costs

Estimated subsystem capital costs for the Type A earth station are as shown in Table 4.10 for quantities 10 and 100. The costs for the latter quantity are derived assuming a 15% cost discount for quantity purchase; costs for the former are based on 1978 off-the-shelf items in small quantities.

It is evident from these estimated costs of present technology and the discussions in Section 1.1 that such an earth station can not presently be economically viable. The key question is therefore: how can these costs be reduced?

There are basically two approaches:

1) Improve the manufacturing process, i.e., utilize mass production techniques.

2) Exploit the technology, i.e., large scale integration (LSI), MIC technology, etc.

In the first approach, production costs will increase as a result of additional capital investments and in the second approach, high development costs will be incurred. To be more cost-effective than the present techniques, a large ($\geq$ 5000) potential market is therefore mandatory for both approaches.

Given the presence of a large market, it is nevertheless clear that the former will result in only a limited overall cost reduction since the recurring costs of subsystem assembly and testing have not been affected. However, by manufacturing integrated subsystems and by utilizing state-of-the-art technology, it is believed that a fairly substantial cost reduction can be achieved, the magnitude of which can only be a source of speculation at present.

SUBSYSTEM	ESTIMATED UNIT COST	
	Quantity 10	Quantity 100
1. 2-m Antenna	$ 4.3K - 6.5K	$ 3.7K - 5.5K
2. 1 Watt Solid-State HPA	2.6K - 3.9K	2.2K - 3.3K
3. 340°K GaAs FET LNA	3 K - 4.6K	2.6K - 3.9K
4. Interfacility Links	1.7K - 2.6K	1.5K - 2.2K
5. RF Channel Filter	0.9K - 1.3K	0.8K - 1.1K
6. Tx Rejection Filter	0.9K - 1.3K	0.8K - 1.1K
7. Up-Converter (non-agile; single stage conversion)	8.5K - 13 K	7.2K - 11 K
8. Down-Converter (non-agile; single stage conversion)	8.5K - 13 K	7.2K - 11 K
9. Common Equipment:		
. Tx IF Amp.	1.7K - 2.6K	1.5K - 2.2K
. AFC + Reference Recovery	3 K - 4.6K	2.6K - 3.9K
. TFU	2.6K - 3.9K	2.2K - 3.3K
. DAMA Controller	4.3K - 6.5K	4.3K - 6.5K
. Metering & Alarm	1.7K - 2.6K	1.5K - 2.2K
. Power Supply	1.3K - 2 K	1.1K - 1.7K
10. Channel Unit	4.3K - 6.5K	3.7K - 5.5K
SUB-TOTAL	$ 49.3K - 74.9K	$ 42.9K - 64.4K
Engineering & Procurement	6 K - 10 K	4.2K - 6.3K
Assembly, Installation & Tests	6 K - 10 K	6 K - 10 K
Documentation	0.3K - 0.5K	0.3K - 0.5K
Shipping (Average)	0.8K - 1.3K	0.8K - 1.3K
TOTAL	$ 62.4K - 96.7K	$ 54.2K - 82.5K

TABLE 4.10 - TYPE A EARTH STATION ESTIMATED SUBSYSTEM COSTS

An example of the latter approach is the development of the MUSAT channel unit (Miller Communications) which essentially incorporates the functions of subsystems 9 and 10 (the Indoor Unit) in Table 4.10. The development cost of the MUSAT channel unit will be in the region of $200K.

Since RF subsystems (Item 1-8, Table 4.10) cost constitutes nearly 49% of overall station cost, it is also clearly desirable that an integrated approach, through the use of MIC (microwave integrated circuit) technology, be adopted in the manufacture of the Outdoor Unit.

Large scale integration of various subsystems not only reduces the unit cost per subsystem but also the high recurring costs for assembly and testing and is hence the key to producing a cost-effective earth station design. This is evident in the integrated approach stressed in the production of low-cost TVRO earth stations for broadcast satellite applications.

4.2.2 Type B Multi-User

In view of its role in providing telecommunication services to several rather than just one household, the Type B station will probably be required to meet a higher service availability objective than the Type A station. This can be achieved by judiciously providing equipment redundancy and adopting appropriate maintenance policies. In cases where standby redundancy of a subsystem or subsystems is provided, it will be necessary to respond to failure of an in-service unit even though automatic switchover to the standby unit avoids a service outage. This imposes the requirement for rapid detection of non-outage producing failures, a potentially difficult problem and a disadvantage of standby redundant configurations.

The diagnostic procedure could be greatly facilitated by using the DAMA controller to also perform diagnostic routines, as mentioned in the previous sub-section, and any switching operations occasioned by in-service unit failure in redundant subsystems.

Three equipment configurations are considered for the Type B station:

1) Configuration IA: 2-meter antenna in tandem with non-redundant transmit and receive paths (Figure 4-4).

2) Configuration IB: 2-meter antenna in tandem with redundant HPA's (10 Watt TWTA) and a non-redundant receive path (Figure 4-5).

3) Configuration II: 3-meter antenna in tandem with parallel redundant transmit paths and a non-redundant receive path (Figure 4-6)*.

Using the subsystem MTBF's assumed in Table 4.11, the 2-of-4 and 4-of-4 circuit availabilities of the three configurations as a function of MTTR are illustrated graphically in Figure 4-7. As in Section 4.2.1, MTTR is assumed to be the same for all subsystems.

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*Use of a 3-meter antenna also upgrades the receive G/T of the Type B station, which could be used to advantage in reducing carrier level, or alternatively in improving link margin, from the hub, and possibly permit Type A to Type B calling on an occasional (reduced margin) basis. It also permits the reception of TV signals from the satellite.

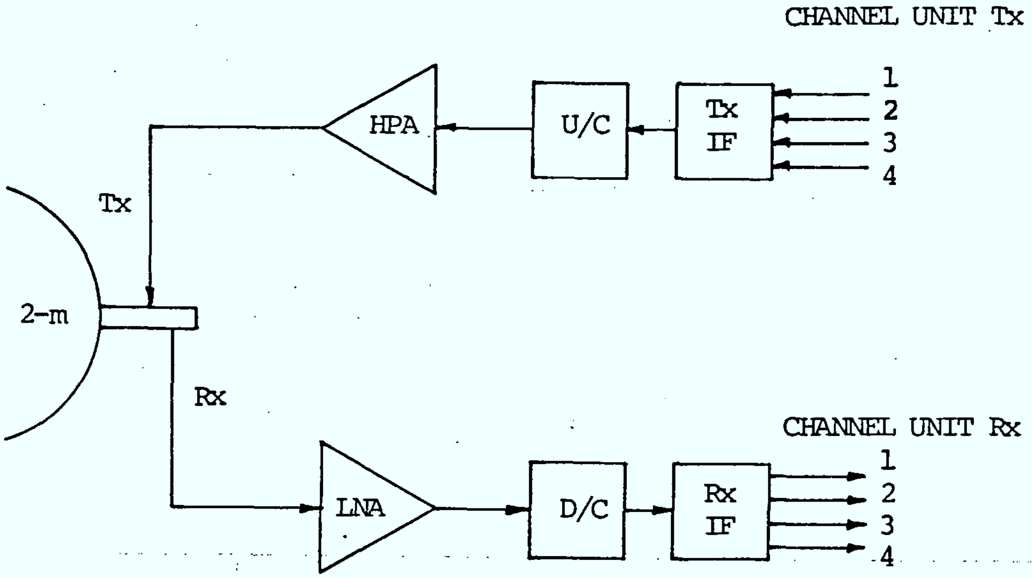

FIGURE 4-4 - CONFIGURATION IA: NON-REDUNDANT TRANSMIT AND RECEIVE PATHS

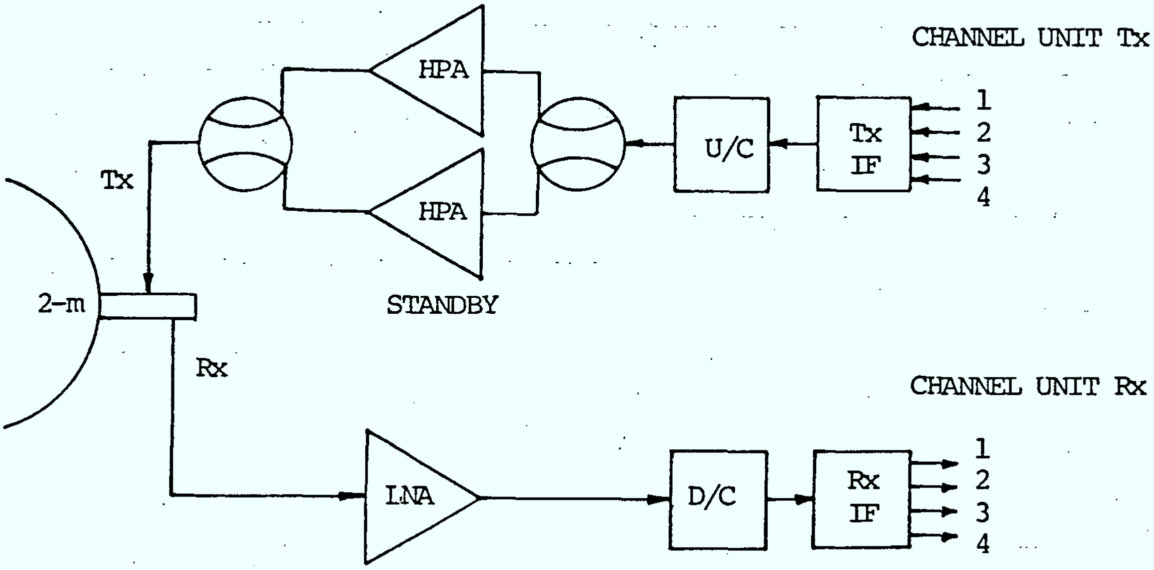

FIGURE 4-5 - CONFIGURATION IB: REDUNDANT HPA AND NON-REDUNDANT RECEIVE PATH

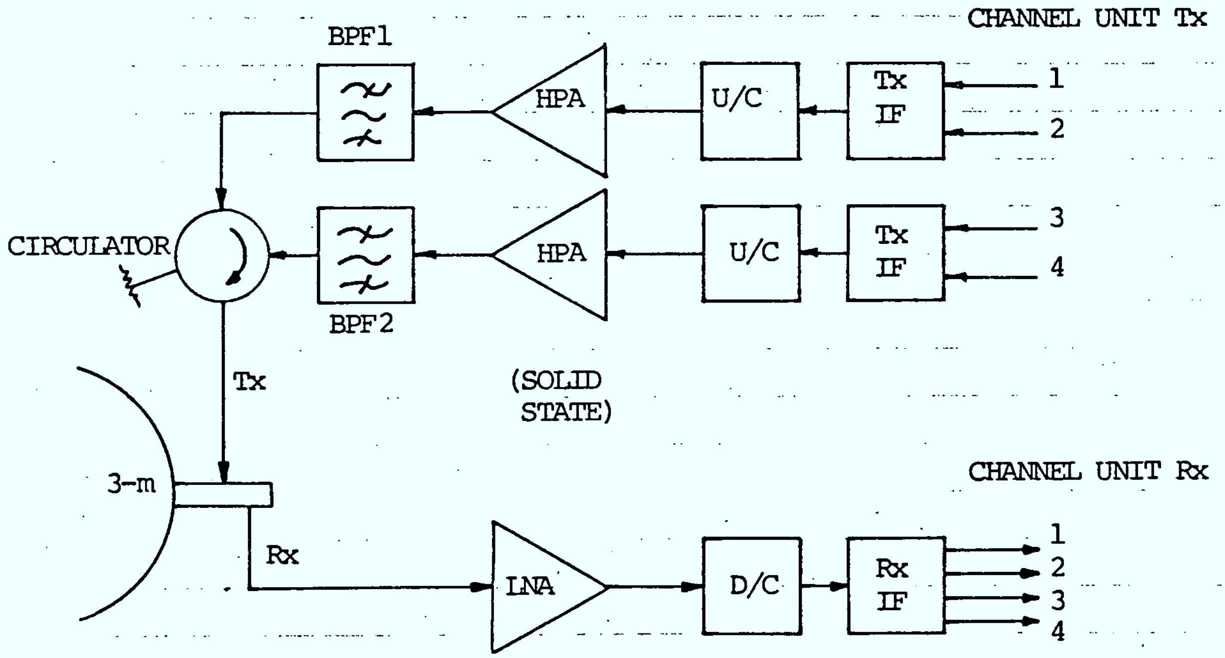

FIGURE 4-6 - CONFIGURATION II: PARALLEL REDUNDANT TRANSMIT PATH, NON-REDUNDANT RECEIVE PATH

		MTBF	AVAILABILITY	
	SUBSYSTEM	(HOURS)	MTTR = 4 HRS.	MTTR = 40 HRS.
1.	Antenna	500,000	0.999992	0.999920
2.	High Power Amplifier (HPA)			
	. Solid-State	66,700	0.999940	0.999401
	. TWTA	8,000	0.999500	0.995025
3.	Low Noise Amplifier (LNA)		0.999932	0.999321
	. Tx Reject Filter +	500,000	0.999992	0.999920
	GaAs FET	66,700	0.999940	0.999401
4.	Up-Converter (non-agile; single stage conversion)	11,600	0.999655	0.996564
5.	Down-Converter (non-agile; single stage conversion)	11,600	0.999655	0.996564
6.	Transmit IF Equipment		0.999871	0.998709
	. IF Combiner	500,000	0.999992	0.999920
	. IF Amp.	33,000	0.999879	0.998789
7.	Receive IF Equipment		0.999718	0.997188
	. AFC + Reference Recovery	14,600	0.999726	0.997268
	. IF Divider	500,000	0.999992	0.999920
8.	Time/Frequency Unit (TFU)	34,400	0.999884	0.998839
9.	DAMA Controller	33,000	0.999879	0.998789
10.	Power Supply Unit	16,600	0.999759	0.997596
11.	Miscellaneous:			
	. Co-ax Switch	200,000	0.999980	0.999800
	. Waveguide Switch	200,000	0.999980	0.999800
	. Bandpass Filter	500,000	0.999992	0.999920
	. Waveguide Circulator	500,000	0.999992	0.999920
	. Waveguide Filter	500,000	0.999992	0.999920

TABLE 4.11 - SUBSYSTEM RELIABILITY DATA

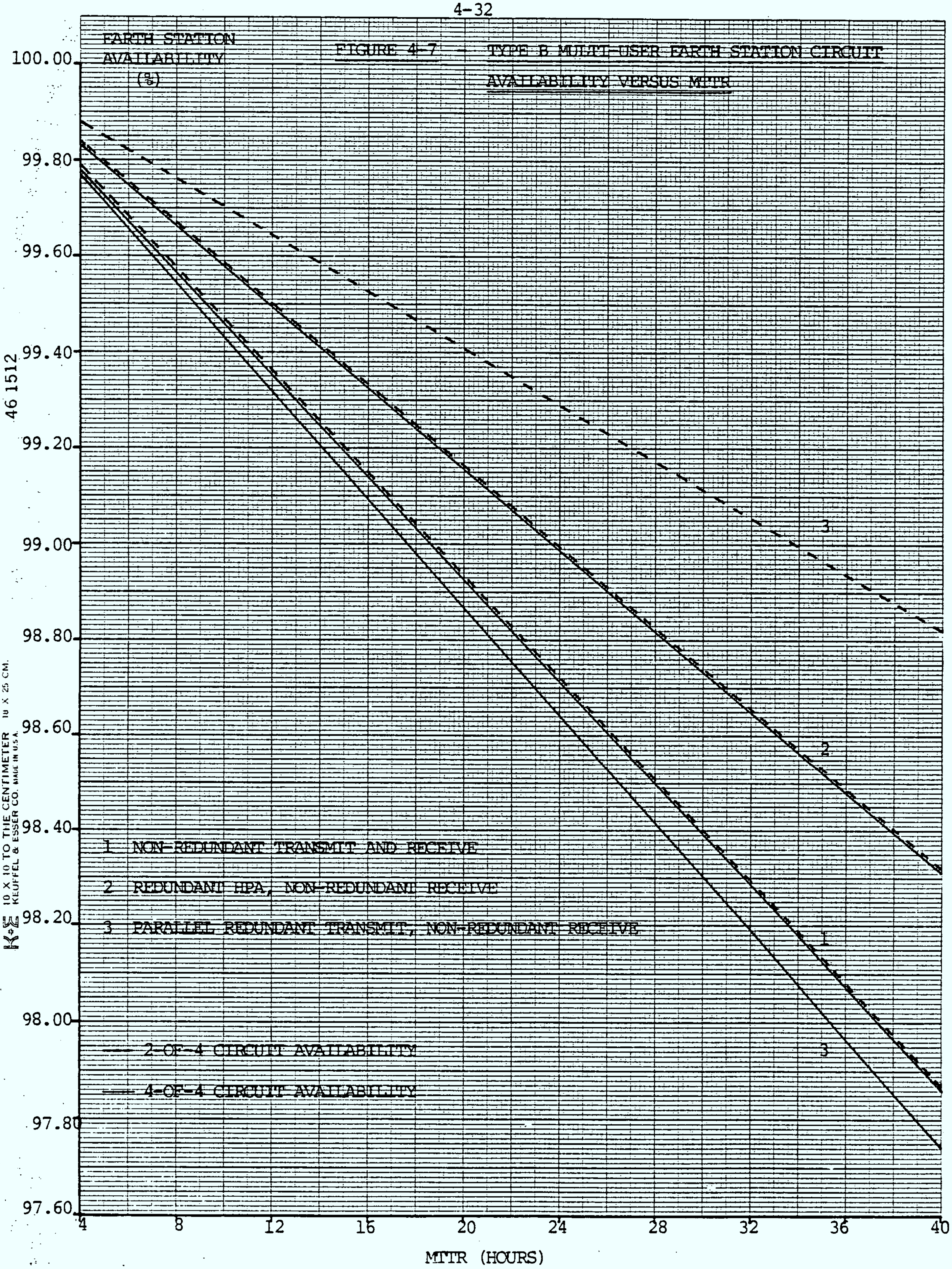

FIGURE 4-7 – TYPE B MULTI-USER EARTH STATION CIRCUIT AVAILABILITY VERSUS MTTR

Since channel unit availability is not dominating, 2-of-4 and 4-of-4 circuit availabilities are nearly identical for configurations IA and IB. In Configuration II, failure of one of the transmitters reduces station capacity from 4 to 2 circuits, implying a much better 2-of-4 than 4-of-4 availability. This is evident in Figure 4-7. Note that parallel redundancy at an unmanned station may offer maintenance advanges over standby redundancy because any failure produces at least a partial (easily detected) service outage.

Estimated earth station costs (quantity 10) for the three configurations are summarized in Table 4.12. From Figure 4-7 and Table 4.12, it is evident that, on the basis of a 2-of-4 circuit availability and an attainable MTTR of 18 hours, each of the three earth station configurations considered represents the minimum cost solution for a given circuit availability as illustrated in Figure 4-8. For quantity 100 earth stations, a 15% reduction can be applied to the derived costs.

Since it is believed unlikely that a 2-of-4 circuit availability of less than about 99.5% will be acceptable to the telephone companies, the most cost-effective earth station configuration will be that of configuration II or variations thereof, e.g., redundant down-converter, etc.

The recommended Type B rural earth station configuration is illustrated in Figure 4-9 and its essential features summarized in Table 4.13. As discussed earlier, this configuration consists of a 3-meter antenna in tandem with parallel redundant transmit paths and a non-redundant receive path. Except for the 3-meter antenna, all communications equipment (GCE) are stored indoors, typically within the local No. 5 end office, for security reasons. Interfacility links (IFL)

SUBSYSTEM	ESTIMATED COST (QUANTITY 10)		
	CONFIGURATION IA	CONFIGURATION IB	CONFIGURATION II
1. Antenna	$ 4.3K - 6.5K	$ 4.3K - 6.5K	$ 5.1K - 7.8K
2. HPA	5.1K - 7.8K	10.2K - 15.6K	5.1K - 7.8K
3. LNA	3 K - 4.6K	3 K - 4.6K	3 K - 4.6K
4. IFL (incl. Dehydrator)	3 K - 4.6K	3 K - 4.6K	3 K - 4.6K
5. Up-Converter (non-agile, single stage conversion)-excluding P.L.O.	6.4K - 9.8K	6.4K - 9.8K	12.8K - 19.6K
6. Down-Converter (non-agile, single stage conversion)-excluding P.L.O.	6.4K - 9.8K	6.4K - 9.8K	12.8K - 19.6K
7. Phase-Locked Oscillator (Quantity 2)	4.2K - 6.6K	4.2K - 6.6K	4.2K - 6.6K
8. Common Equipment:			
. Tx IF Amp.	1.7K - 2.6K	1.7K - 2.6K	3.4K - 5.2K
. IF Combiner	0.4K - 0.7K	0.4K - 0.7K	0.4K - 0.7K
. IF Splitter	0.4K - 0.7K	0.4K - 0.7K	0.4K - 0.7K
. AFC + Ref. Recovery	3 K - 4.6K	3 K - 4.6K	3 K - 4.6K
. TFU	2.6K - 3.9K	2.6K - 3.9K	2.6K - 3.9K
. DAMA Controller	4.3K - 6.5K	4.3K - 6.5K	4.3K - 6.5K
. Metering & Alarm	1.7K - 2.6K	1.7K - 2.6K	1.7K - 2.6K
. PSU	1.3K - 2 K	1.3K - 2 K	1.3K - 2 K
9. Channel Unit	17.2K - 26 K	17.2K - 26 K	17.2K - 26 K
10. Co-ax Switch		0.4K - 0.7K	
11. RF Bandpass Filter	0.9K - 1.3K	0.9K - 1.3K	0.9K - 1.3K
12. Waveguide Switch		1.3K - 2 K	
13. Waveguide Circulator			0.9K - 1.3K
14. Waveguide BPF			1.8K - 2.6K
15. Miscellaneous Hardware (VF jackfield, rack mount, etc.)	1.7K - 2.6K	1.7K - 2.6K	1.7K - 2.6K
SUB-TOTAL	$67.6K - 103.2K	$74.4K - 113.7K	$85.6K - 130.6K

TABLE 4.12 - TYPE B RURAL EARTH STATION ESTIMATED SUBSYSTEM COSTS (QTY. 10) CONT'D

SUBSYSTEM	ESTIMATED COST (QUANTITY 10) CONFIGURATION IA	CONFIGURATION IB	CONFIGURATION II
Sub-Total Brought Forward	$67.6K - 103.2K	$74.4K - 113.7K	$ 85.6K - 130.6K
Engineering & Procurement	7.5K - 12.5K	7.5K - 12.5K	7.5K - 12.5K
Assembly, Installation & Tests	7.5K - 12.5K	7.5K - 12.5K	7.5K - 12.5K
Documentation	0.3K - 0.5K	0.3K - 0.5K	0.3K - 0.5K
Shipping (Average)	0.8K - 1.3K	0.8K - 1.3K	0.8K - 1.3K
TOTAL	$83.7K - 130.0K	$90.5K - 140.5K	$101.7K - 157.4K

TABLE 4.12 - TYPE B RURAL EARTH STATION ESTIMATED SUBSYSTEM COSTS (QTY. 10)

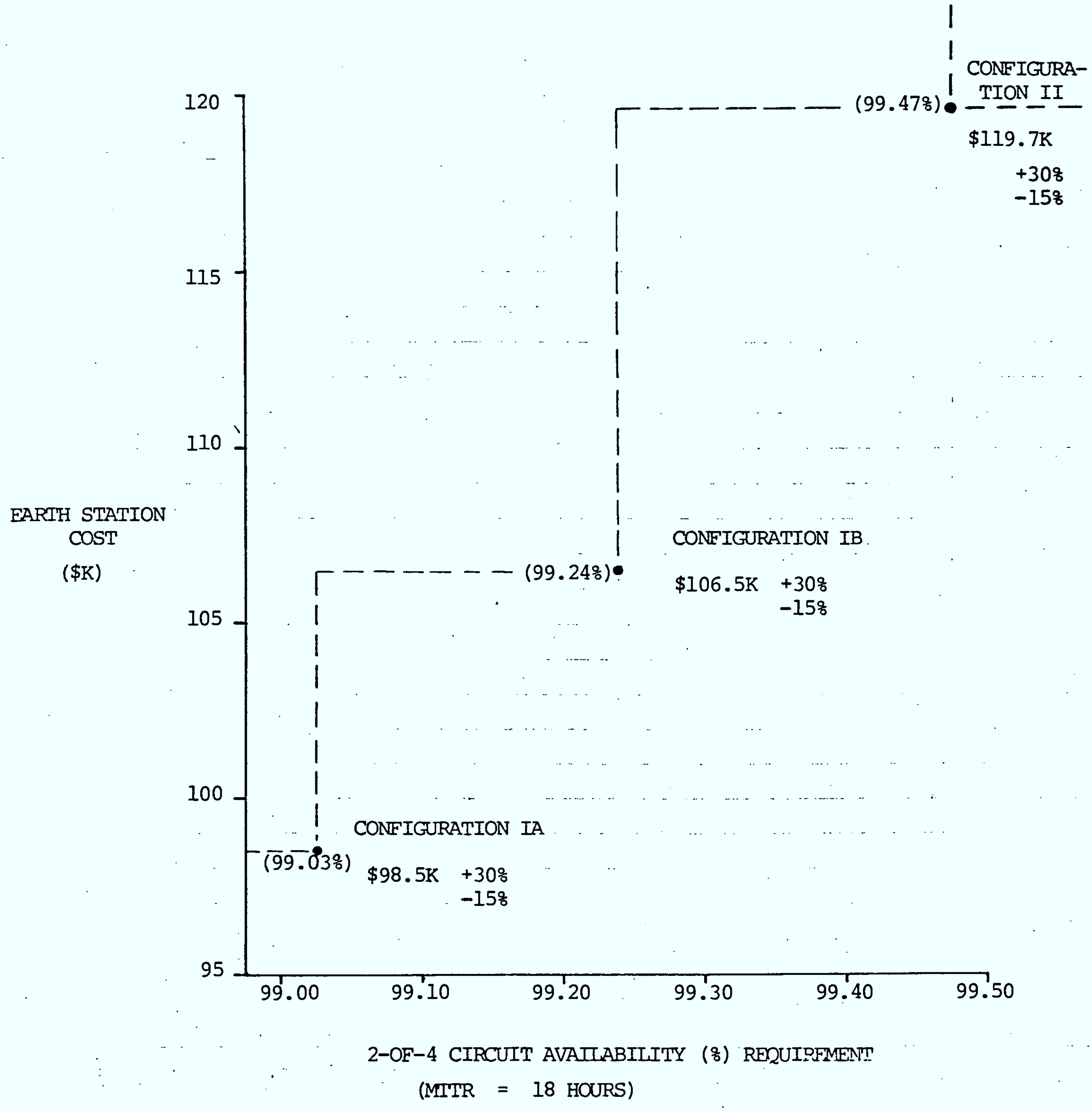

FIGURE 4-8 - MINIMUM EARTH STATION COST VERSUS 2-OF-4 CIRCUIT AVAILABILITY (MTTR = 18 HOURS)

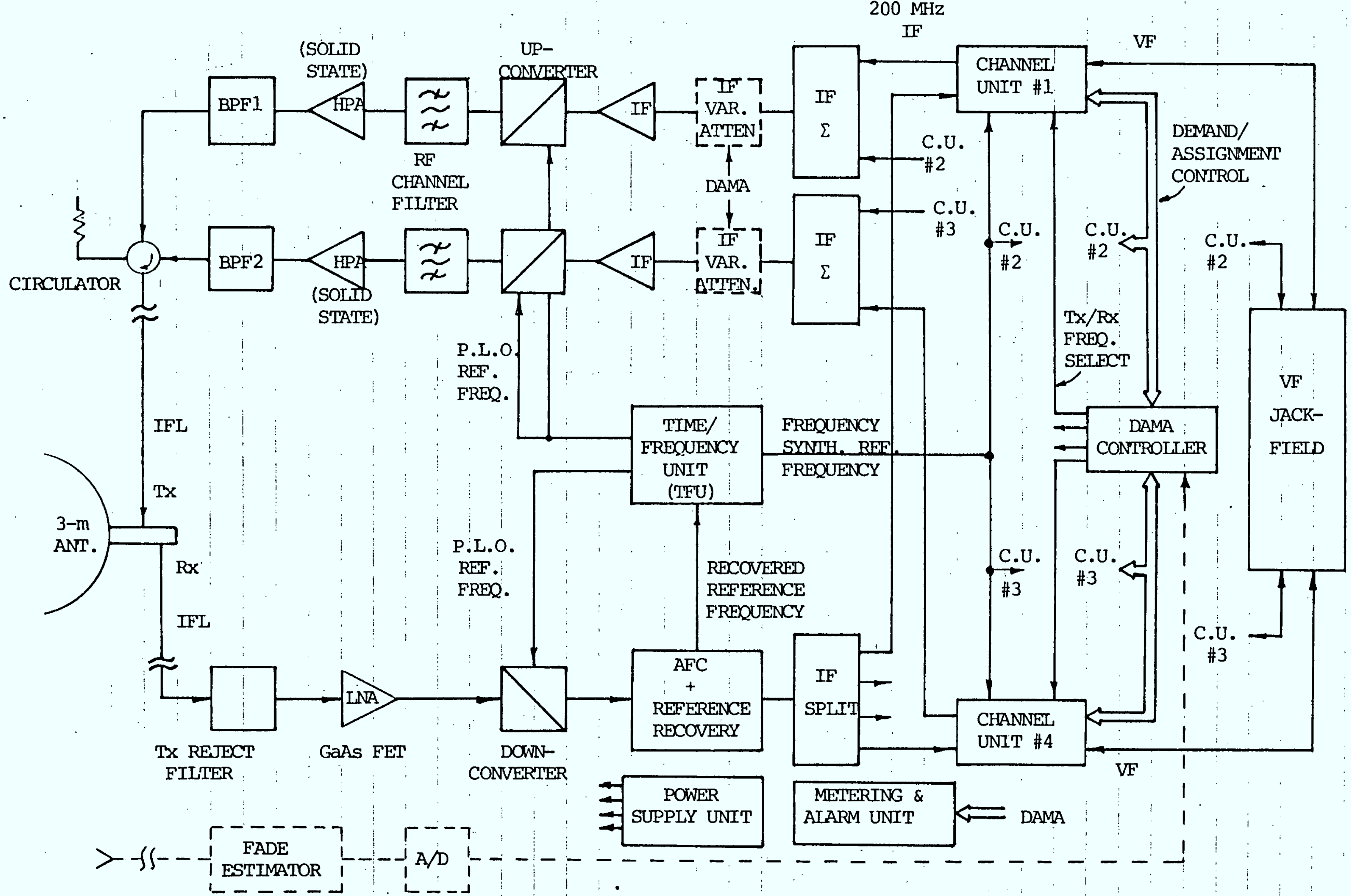

FIGURE 4-9 - TYPE B MULTI-USER RURAL EARTH STATION CONFIGURATION

Antenna Size	3-meters
Station G/T	~ 22.8 dB/°K
Low Noise Amplifier (LNA)	~ 340°K GaAs FET
High Power Amplifier (HPA)	2 x 1 Watt Solid-State
Transmission Capability	Four (4) SCPC Carriers (FM or 32 kbps Δ-mod)
Frequency Agility	Non-Agile
Access Technique	Demand-Assignment Multiple Access (DAMA)*
Equipment Configuration	Parallel Redundant Transmit, Non-Redundant Receive

TABLE 4.13 - TYPE B RURAL EARTH STATION CHARACTERS

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*See discussions on frequency restrictions of this earth station configuration (Section 2.3.1).

connect the outdoor antenna to the GCE. The IFL consists of low-loss elliptical waveguides which are dehydrated to minimize RF losses. Note that with the exceptions of the parallel redundant transmit paths and channel capacity, this station is very similar operationally to the Type A earth station described in Section 4.2.1 and hence a further detailed description will not be undertaken.

An important restriction of this configuration with regards to frequency selection and choice of center frequencies for bandpass filters BPF1 and BPF2 has previously been discussed in Section 2.3.1. Both the up-converter and down-converter correspond identically to those of the Type A station; i.e., they are non-frequency-agile and utilize a single stage of up- or down-conversion.

The DAMA controller interfaces with all four channel units and hence is able to utilize any of the four as the DACC channel unit depending on traffic activity. In addition, it selects the required transmit/receive frequency pair for each channel unit in a certain sequence as described in Section 2.3.1.

The output of the voice-frequency (VF) jackfield consists of four duplex (4-wire) voice circuits which are routed directly to the local switch in the collocated No. 5 end office.

4.2.3 Gateway Station

In view of the critical importance of the gateway station to the operation of a 2-carrier-level, hubbed SCPC system, it must necessarily incorporate expensive features to ensure its operational integrity. Such a station might be required to perform the dual role of operations center for the SCPC network as well as being the distribution center for the national television networks.

For the link calculations in Section 4.1, a station G/T of 26.5 dB/°K, obtained with a 4.57-meter antenna and a 340°K GaAs FET LNA, has been arbitrarily assumed. It is known [28] that Telesat Canada intends to procure 4.57-meter earth stations for network TV distribution at 12/14 GHz but its intended technical specifications are as yet unknown.

Some of the functions which each gateway station (one per beam) is expected to perform are:

1) Provide access to and from the terrestrial switched network.

2) Switch double hopped rural-to-rural calls within the beam.

3) Provide centralized DAMA control of its SCPC network within the beam.

4) Provide up-link power control of the gateway-to-rural earth station carriers (see Section 2.3.4).

5) Transmission of the AFC system pilot and the distribution of an ultra-stable reference frequency by the two pilot schemes described in Section 2.5. Double or triple equipment redundancy will be required to ensure very high reliability in view of the critical importance of these pilots to the entire system operation.

6) Possibly incorporate the functions of the central maintenance center.

7) Possibly the reception and the re-distribution of national network TV transmissions within its spot beam.

Other possible features of the gateway station are:

1) Fully redundant equipment configuration.

2) Fully manned operation.

3) Auto-tracking facilities to minimize link fades due to satellite drift.

4) Dual polarization transmission capability (for Anik C operation).

5) Standby power facilities, e.g., diesels together with a UPS (uninterrupted power supply) system.

5.0 CONCLUSIONS

The following summarizes briefly results obtained in the study:

(i) A hubbed system which restricts or entirely precludes direct single hop rural to rural calling is more economic and acceptable from an up-link interference standpoint than a fully connected system. With 2-meter antennas and a 3.5° satellite spacing, interference into 90 Mbps and two carrier TV traffic (anticipated on Anik C) causes less than 0.1 dB of equivalent C/N degradation. Antenna diameters less than 2 meters are not recommended either on the basis of adjacent satellite interference or cost-effective system design.

(ii) Down-link adjacent satellite interference into the rural earth station will not be a consideration providing large, potentially narrow band (e.g. TV) cochannel carriers are avoided. The vulnerability of the system to such interference is a result of the narrow band, low power nature of SCPC transmission rather than the small earth station diameter.

(iii) Up-link power control (on carriers transmitted from the hub only) and voice activation are recommended as a means of enhancing space segment utilization with little penalty in earth segment cost. The Anik C bandwidth limited transponder capacity (2400 channels) is approached using either companded FM or 32 kbps delta/4 phase CPSK modulation and 2 meter antennas.

(iv) Demand assignment is essential if the satellite system is to serve subscribers directly. Under such circumstances, cost of service is totally dominated by earth segment cost. This differs from most existing satellite systems in which the transponder lease charge is dominant.

(v) A 4 channel, 3 meter multi-user earth station providing a circuit availability of 99.5% and capable of being fitted to receive two channels per transponder TV can be constructed and installed in quantity ten at a unit cost (not including development, site preparation, provision of prime power or sales taxes) of about $100,000. Assuming a five year amortization period, this implies a cost per telephone per year of $5,000.

(vi) The cost of a single user 2 meter earth station is estimated to be at least $60,000 in quantity 10 to 100. This implies a cost per telephone per year of $15,000, or three times that for multi-user service. Furthermore, the station's ability to receive TV on a 2 channel per transponder basis would be limited.

(vii) A community terminal providing 4 to 8 telephone channels (at a per channel annual cost of $3000 - $5,000), with an option to also provide one channel of TV (at an incremental annual cost of say $1,000), appears an attractive means of extending telephony and TV service to rural areas. Scattered households can gain access to such a community earth station (and each other) by subscriber radio or other means. The alternative of providing each telephone subscriber with his own earth station is not economically viable at present although it might be applied in special cases of public or individual need.

(viii) The cost of service for the hubbed SCPC system proposed in this study is expected to be less than half that of existing 4/6 GHz SCPC systems, neglecting development and applying identical return on investment criteria. Earth segment and space segment cost reductions have resulted from three factors:

- i use of an advanced 12/14 GHz, spot beam satellite;
- ii optimization of the system design including application of novel frequency control, power control and output combining techniques;
- iii application of new earth station technology such as solid state HPA and advanced channel unit designs.

Little further cost saving is believed achievable in the system design and exploitation of near term technology at the subsystem level.

(ix) For very large quantity (> 5000) procurement, additional cost reductions are achievable through the use of large scale integration and automated production, integration and testing. While it is more difficult to responsibly estimate unit price assuming such large quantities, a factor of two reduction in cost can be assumed for planning purposes. In the case of the 4 channel multi-user terminal this results in an earth station capital cost of $50,000, or an annual cost per telephone of $2,500.

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APPENDIX A

ADJACENT SATELLITE INTERFERENCE ANALYSIS

A.1 Introduction

With the proliferation of geostationary communications satellites and the limited geostationary orbit-spectrum available (Figure A-1), there has been a growing concern about the rapid depletion of this resource and the need for more efficient utilization.[1,2,3] This applies in particular to SCPC systems using small aperture antennas.[4,5]

The primary limiting factor in the efficient utilization of the orbital arc is one of mutual interference between the various satellite systems. Figure A-2 illustrates the interference paths (dotted lines) for the case of two adjacent satellite systems. Two types of interference paths arise:

(1) Up-link interference through the side lobes of transmitting antenna A into the receiver of satellite Y and, similarly, from antenna B into satellite X;

(2) Down-link interference from satellite X into the side lobes of receiving antenna D and, similarly, from satellite Y into antenna C.

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[1] Sawitz, P.H., "Spectrum-Orbit Utilization - An Overview", NTC '75, New Orleans, December 1975, pp. 43-1 to 43-7.

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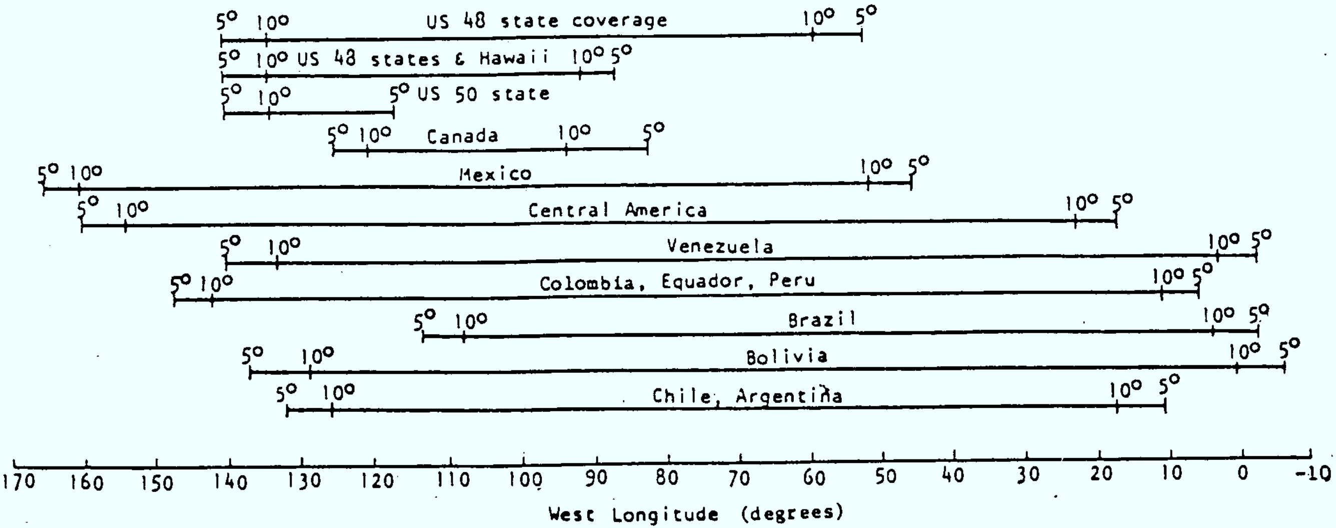

FIGURE A-1. Usable Orbital Arcs for Various Countries in ITU Region 2

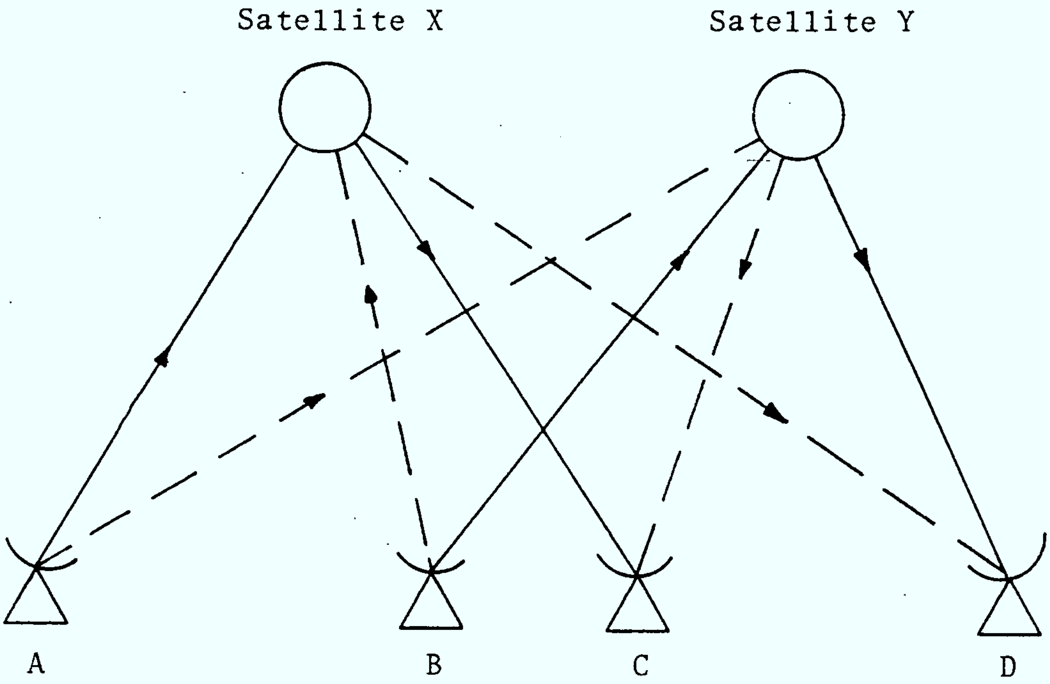

FIGURE A-2. Satellite Interference Geometry

Since the directivity of the ground antenna is the primary means of discriminating between users of the same frequencies, polarization, and area of coverage, it is clear that the radiation pattern of the earth station antenna is the single most important factor in determining how closely satellites can be spaced and, thus, how much frequency re-use is possible in a given orbital arc.

Antenna side lobe levels are not, in fact, easily predictable. The CCIR has recommended that, for interference studies, a standard side lobe envelope (CCIR Rec. 465-1)[6] be used. For the fixed satellite service operating in the 2 to 10 GHz frequency band and an antenna diameter-to-wavelength (D/λ) ratio greater than 100, the recommended gain pattern is given by:

$$G(\theta) = 32 - 25 \log \theta \ \text{dB}$$

where θ = off-axis angle in degrees and is greater than 1°.

While the problem of efficient orbit utilization and mutual interference between satellites is of current concern mainly to the users of the 4/6 GHz satellite frequency band, it is inevitable that these concerns will also arise with the higher frequency bands (notably the 12/14 GHz band). This fact is highlighted by the imminence of such 12/14 GHz satellites as the Anik B (late 1978), the SBS satellite (mid-1980) and the Anik C series of satellites (commencing in 1980-81).

In this Appendix, a rudimentary analysis of the effects of both up-link satellite interference from and down-link interference into a rural SCPC network is presented. Assumptions which are pertinent to the ensuing discussions are:

(1) The interfering and the interfered with satellites are Anik C types.

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[6] CCIR Green Book Vol. IV, XIII'th Plenary Assembly, Geneva, 1974, pp. 155-156.

(2) Satellite spacing is 3.5°.

(3) Direct rural to rural calling is permitted (i.e., homogeneous or equal carrier system assumed).*

(4) SCPC carriers are distributed randomly across the full satellite transponder (BW = 54 MHz) operating at a multi-carrier input backoff of 11 dB.

(5) A co-channel, adjacent satellite 90 Mbps message carrier occupies the entire transponder bandwidth of 54 MHz and operates at a satellite input backoff of 2 dB (Telesat specification).

(6) A half-transponder TV carrier occupies a noise bandwidth of 27 MHz and a Carson Rule Bandwidth of approximately 24.6 MHz at a per carrier input backoff of 7 dB.

In the following sections, carrier-to-interference (C/I) ratios are derived for the case of up-link interference from a homogeneous SCPC system into an adjacent satellite in which two types of co-channel carriers are considered: (a) high speed (90 Mbps) message; and (b) half-transponder TV. Both types of traffic will be on Anik C[7]. In addition, the C/I values are derived for two sizes of SCPC antennas, viz., 1-meter and 2-meters.

In the case of down-link interference into an SCPC system, an expression is derived for the resulting increase in noise or, equivalently, the reduction in receive carrier-to-thermal

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*By using a 2-carrier level, hubbed SCPC system, as discussed in Section 3.0, the required transmit EIRP of the rural terminal and hence off-axis interference, can be reduced by 4 to 5 dB relative to that required for a homogeneous (equal carrier level) system.

[7] Weese, D.E., "The Canadian Domestic Satellite Communication System - Present and Future", INTELCOM '77, Atlanta, October 1977, pp. 157-159.

noise ratio (C/N) at the input to the SCPC station demodulator. The effects of various types of co-channel interferers on the SCPC carrier are briefly discussed.

A.2 Up-Link Interference to Adjacent Satellites

In this section, the carrier-to-interference (C/I) ratio into an adjacent satellite system is derived. Specific cases which have been evaluated are for a SCPC system consisting of

- 1-meter antennas
- 2-meter antennas

interfering with

- 90 Mbps message carrier
- a half-transponder TV carrier.

Referring to Figure A-3, the per carrier interfering flux density at the adjacent satellite is given by:

$$\text{Per carrier } \phi_{adj} = \text{EIRP} - G(0) + G(\theta)^{*} - 10 \log (4\pi R_2^2) \quad \text{dBW/m}^2 \qquad (1)$$

where

EIRP = transmit EIRP of SCPC earth station, in dBW

G(0) = on-axis gain of SCPC antenna

$$= 10 \log \left(\frac{\pi D}{\lambda}\right)^2 \eta \quad \text{dBi}$$

and

D = antenna diameter, in meters

λ = wavelength at the transmit frequency, in meters

η = antenna efficiency

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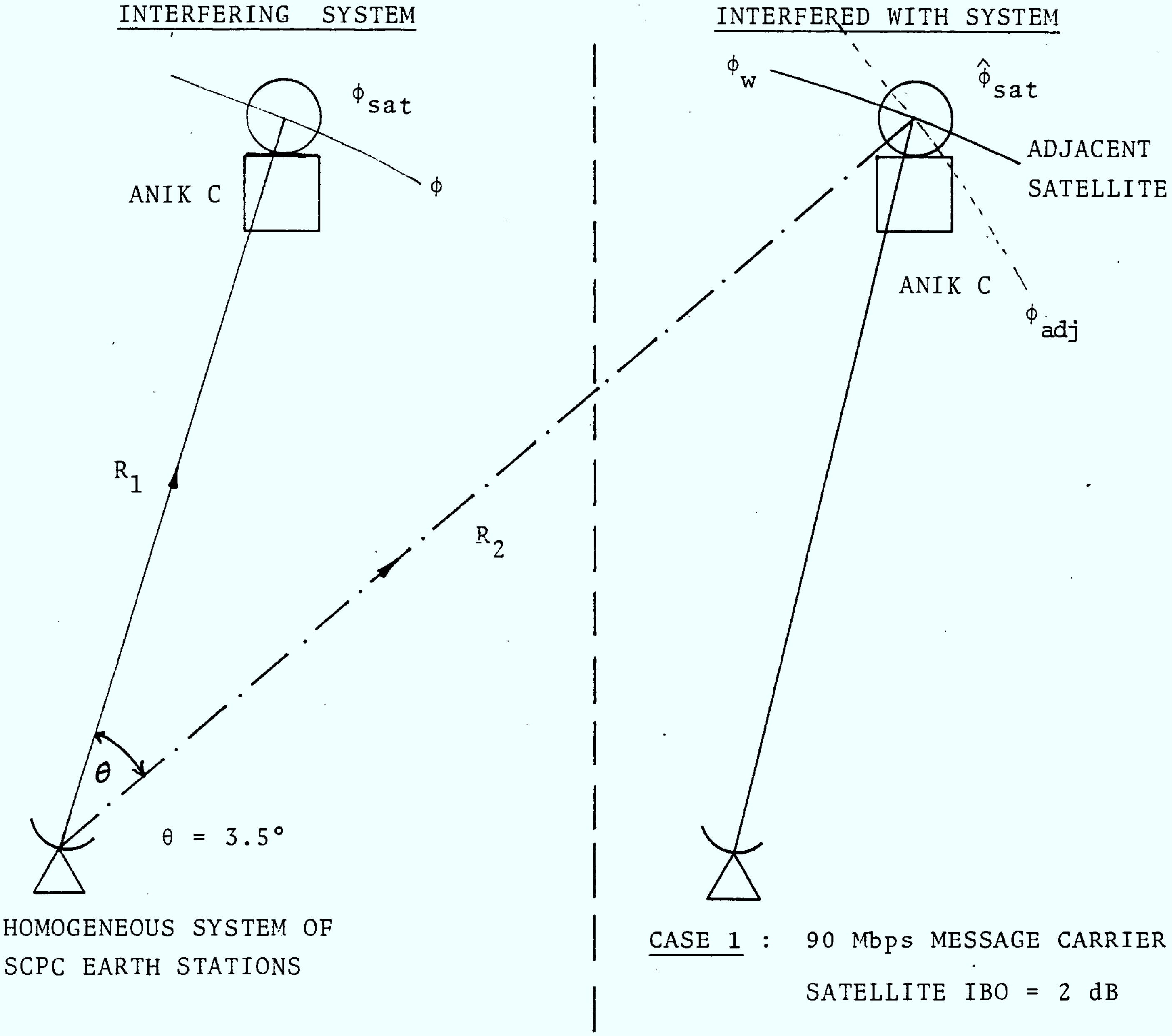
[*] Antenna discrimination is defined as G(0) - G(θ).



CASE 1 : 90 Mbps MESSAGE CARRIER
SATELLITE IBO = 2 dB

CASE 2 : HALF-TRANSPONDER TV
SATELLITE IBO PER CARRIER = 7 dB

FIGURE A-3 UPLINK INTERFERENCE INTO AN ADJACENT SATELLITE

$G(\theta)$ = off-axis gain of antenna at angle θ

$$= \begin{cases} 32 - 25 \log \theta \text{ , } D/\lambda > 100 \text{ (CCIR Rec. 465-1)} \\ 52 - 10 \log (D/\lambda) - 25 \log \theta \text{ , } D/\lambda < 100 \text{ (CCIR Rep. 391-2}^{8}\text{)} \end{cases}$$

θ = geocentric angular separation of the satellites, in degrees*

R_1 = range to satellite carrying SCPC traffic

R_2 = range to adjacent satellite
$\cong R_1$ for small values of θ

Equation 1 can be expressed as:

$$\text{Per carrier } \phi_{adj} \cong \text{EIRP} - 10 \log (4\pi R_1) - G(0) + G(\theta)$$
$$= \phi - G(0) + G(\theta)$$
$$= \phi_{sat} - \text{IBO}_{pc} - G(0) + G(\theta) \text{ dBW/m}^2 \qquad (2)$$

where

ϕ = flux density per carrier at wanted satellite, in dBW/m^2

ϕ_{sat} = single carrier saturation flux density of wanted satellite, in dBW/m^2

IBO = satellite input backoff per SCPC carrier, in dB

Re-arranging equation (2):

$$\boxed{\text{Per carrier } \phi_{adj} = \phi_{sat} + G(\theta) - G(0) - \text{IBO} \text{ dBW/m}^2} \qquad (3)$$

---

[8] CCIR Green Book Vol. IV, XIII'th Plenary Assembly, Geneva, 1974, pp. 176-180.

*Strictly speaking, θ is the topocentric angle but since it approximates the geocentric angle, these two angles are used interchangeably.

∴ The total interfering flux density at the adjacent satellite due to m SCPC carriers is given by:

$$\left[\phi_{adj}\right]_{tot} = \phi_{adj} + 10 \log m$$

or

$$\boxed{\left[\phi_{adj}\right]_{tot} = \phi_{sat} + G(\theta) - G(0) - IBO + 10 \log m \quad dBW/m^2} \qquad (4)$$

The flux density of the wanted signal at the adjacent satellite is given by:

$$\phi_w = \hat{\phi}_{sat} - IBO_w \quad dBW/m^2 \qquad (5)$$

where

$\hat{\phi}_{sat}$ = single carrier saturation flux density of the adjacent satellite, in dBW/m^2

∴ The carrier-to-interference ratio is given by:

$$\frac{C}{I} = \phi_w - (\phi_{adj})_{tot}$$

$$= \left[\hat{\phi}_{sat} - \phi_{sat}\right] - IBO_w - G(\theta) + G(0) + IBO - 10 \log m \quad dB \qquad (6)$$

Since it has been assumed that both satellites are Anik C types, then

$$\hat{\phi}_{sat} = \phi_{sat} \qquad (7)$$

Also the SCPC transponder multi-carrier input backoff is given by:

$$IBO_{int} = IBO - 10 \log m \qquad (8)$$

Thus from equation (6):

$$\boxed{\frac{C}{I} = G(0) - G(\theta) - (IBO_w - IBO_{int})\ \text{dB}} \qquad (9)$$

By substituting the various parameters previously stated into equation (9), the C/I for the various cases can be derived. Note that for both sizes of SCPC antennas, the $G(\theta)$ used is that given in CCIR Report 391-2[8] since $D/\lambda < 100$, i.e.:

$$G(\theta) = 52 - 10 \log (D/\lambda) - 25 \log \theta \qquad (10)$$

The results of the calculations can be summarized as follows:

	Interference Type	C/I (dB)
1)	1-m → 90 Mbps Message	28.3
2)	1-m → Half-Transponder TV	26.7
3)	2-m → 90 Mbps Message	37.3
4)	2-m → Half-Transponder TV	35.7

Recommendations for allowable interference levels or protection ratios (C/I) have not been established as yet by the CCIR for SCPC into SCPC, SCPC into TV, TV into SCPC or SCPC into high speed digital traffic. It is fairly certain, however, that the C/I protection ratios will be greater than 30 dB (possibly in the order of 34 to 36 dB). If such is the case, then it appears that, from an up-link interference standpoint, the smallest antenna size which might be considered for use in a fully connected 12/14 GHz rural SCPC system is about 2-meters.

A.3 Down-Link Interference From Adjacent Satellites

For the case of down-link interference (Figure A-4) into an SCPC earth station, it is required that the C/I ratio at the demodulator input due to the adjacent satellite system(s) be computed. This interference can occur both on the up-link (EIRP transmitted off-axis to the SCPC satellite) and down-link (EIRP received off-axis from an adjacent satellite) as indicated in Figure A-2.

Up-link interference is not considered because:

(1) It is expected to be much less significant than down-link interference.

(2) It is not influenced by the design of the SCPC earth segment.

The following parameters for a homogeneous SCPC system and an interfering adjacent satellite system can be defined as follows:

Homogeneous SCPC System -

m = number of simultaneous SCPC carriers

OBO = satellite output backoff per carrier

$G(\theta)$ = earth station receive gain at an off-axis of θ degrees, in dB

T_s = earth station receive system noise temperature, in °K

B = SCPC noise bandwidth, in Hz

10 log k = -228.6 dBW/°K-Hz where k is Boltzmann's constant

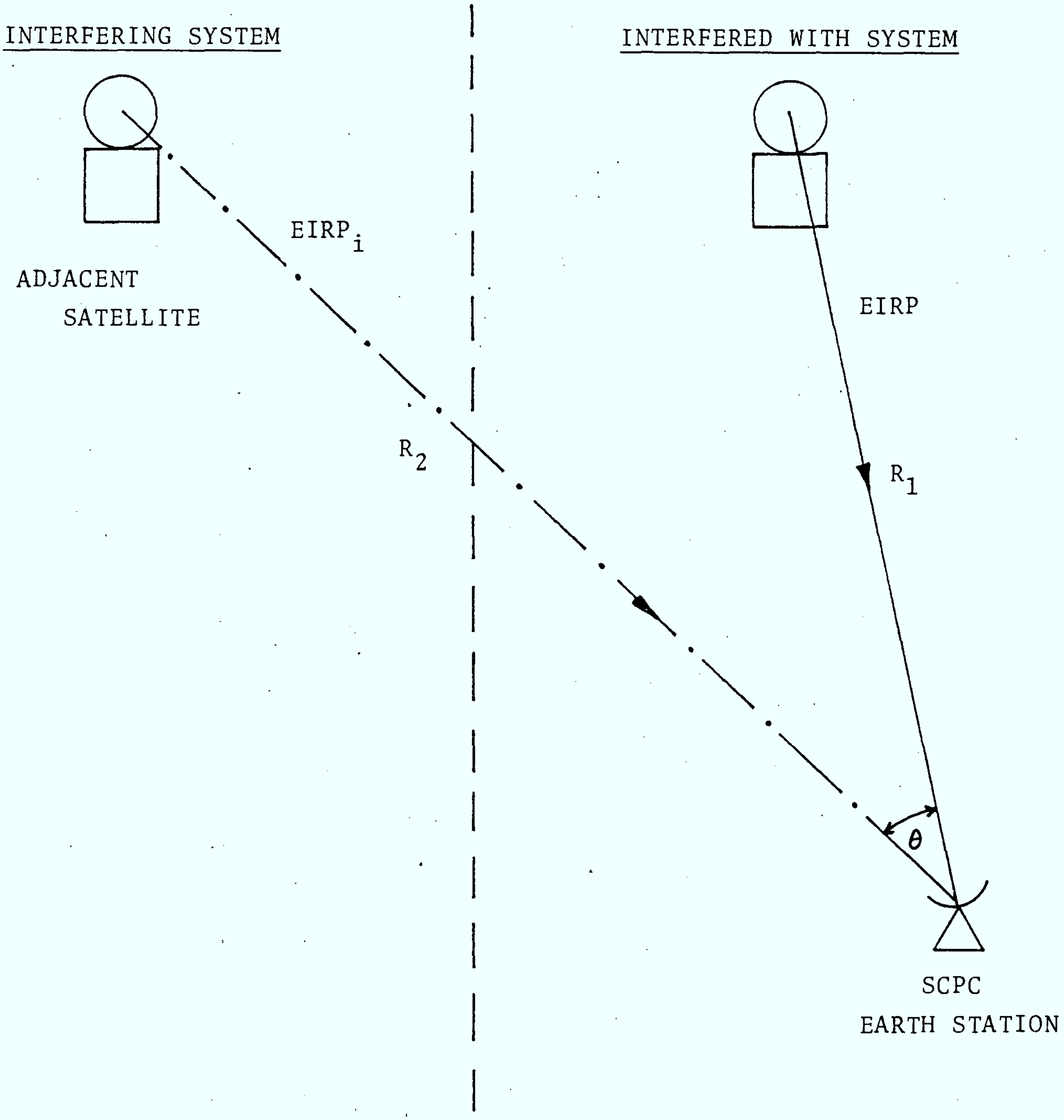


FIGURE A-4 DOWNLINK INTERFERENCE FROM AN ADJACENT SATELLITE

Interfering System -

$P(f)$ = equivalent isotropic radiated flux density (watts/Hz) from interfering satellite

For a satellite spacing of θ degrees, under clear weather conditions, the down-link carrier-to-noise and carrier-to-interference ratio are given by

$$\left[\frac{C}{N}\right]_{down} = EIRP - OBO + 10 \log m - 10 \log B + G(0) - 10 \log T_s - FSL_d - 10 \log k$$

and

$$\left[\frac{C}{I}\right]_{down} = EIRP - OBO + 10 \log m + G(0) - G(\theta) - EIRP_i$$

where

$$EIRP_i = 10 \log \int_{f_c - \frac{1}{2}B}^{f_c + \frac{1}{2}B} P(f) \, df$$

is the interfering EIRP from the adjacent satellite.

The difference between the interference and thermal noise powers at the demodulator input is then given by:

$$\begin{aligned} \Delta &= \frac{C}{N} - \frac{C}{I} \\ &= EIRP_i + G(\theta) - 10 \log B - 10 \log T_s - FSL_d - 10 \log k \\ &= I_o + G(\theta) - 10 \log T_s - FSL_d - 10 \log k \qquad (1) \end{aligned}$$

where I_o is the interfering EIRP per Hertz.

On an RF power addition basis, the increase in noise due to interference is simply $1 + 10^{0.1\Delta}$ which depends only on:

(1) The system noise temperature of the receiving station, T_s

(2) The EIRP per Hertz from the interfering satellite, I_o

(3) The receiving antenna gain towards the interfering satellite, $G(\theta)$

For $D/\lambda > 100$, the expression for the reduction in C/N or, equivalently, the increase in noise, is not a function of antenna diameter since typically[6]

$$G(\theta) = 32 - 25 \log \theta$$

However, for $D/\lambda < 100$, substitution of the modified equation for $G(\theta)$[8], i.e.,

$$G(\theta) = 52 - 10 \log (D/\lambda) - 25 \log \theta$$

is probably more realistic and, for these cases, the expression for $G(\theta)$ does indicate a relationship with antenna diameter.* To be consistent with the previous section on up-link interference, the modified expression for $G(\theta)$ will also be used here.

Since the use of 1-meter antennas appears inappropriate for a rural SCPC system because of up-link interference considerations, only the 2-meter antenna will be considered. The total C/I due to co-channel interference from other adjacent satellites at orbital spacings of 3.5° can be approximated by multiplying the C/I due to one adjacent satellite by 2.5 (4 dB). Using this approximation, the total increase in noise at the demodulator input vs. interfering EIRP per kHz for down-link adjacent satellite interference for an off-axis angle of 3.5° and system noise temperatures ranging from 100 to 500°K has been plotted in Figure A-6 for the 2-meter antenna.

---

*For the 2-meter antenna, the difference in $G(\theta)$ for the two different expressions is quite small for the same off-axis angle θ. For example, the difference in $G(\theta)$ on the transmit side for $f = 14.25$ GHz ($\lambda = 0.021$m) and $\theta = 3.5°$ is 0.2 dB; on the receive side, where $f = 12$ GHz ($\lambda = 0.25$m), the difference is 1 dB.

It is clear from Figure A-6 that the effect of down-link adjacent satellite interference into the SCPC earth station is small providing the receive system noise temperature is not too low.

Baseband Distortion

The effect of the adjacent satellite interference on the SCPC carrier is generally to corrupt the demodulated baseband signal. The extent of this corruption depends 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 wide-band interference
2) Stationary narrow-band interference
3) Non-stationary interference

In stationary wide-band interference, the interfering carrier has a much wider bandwidth than the SCPC carrier bandwidth and its effect is therefore equivalent to that of thermal noise*.

The reduction in effective down-link carrier-to-noise ratio due to the interference, or the corresponding increase in G/T required to compensate for its effect, is therefore given by the results of Figure A-6.

The following types of interfering traffic fall into the wide-band category:

- FDM/FM/FDMA (with energy dispersal present during light loading)
- Single carrier FDM/FM (e.g., 960 channel message)

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

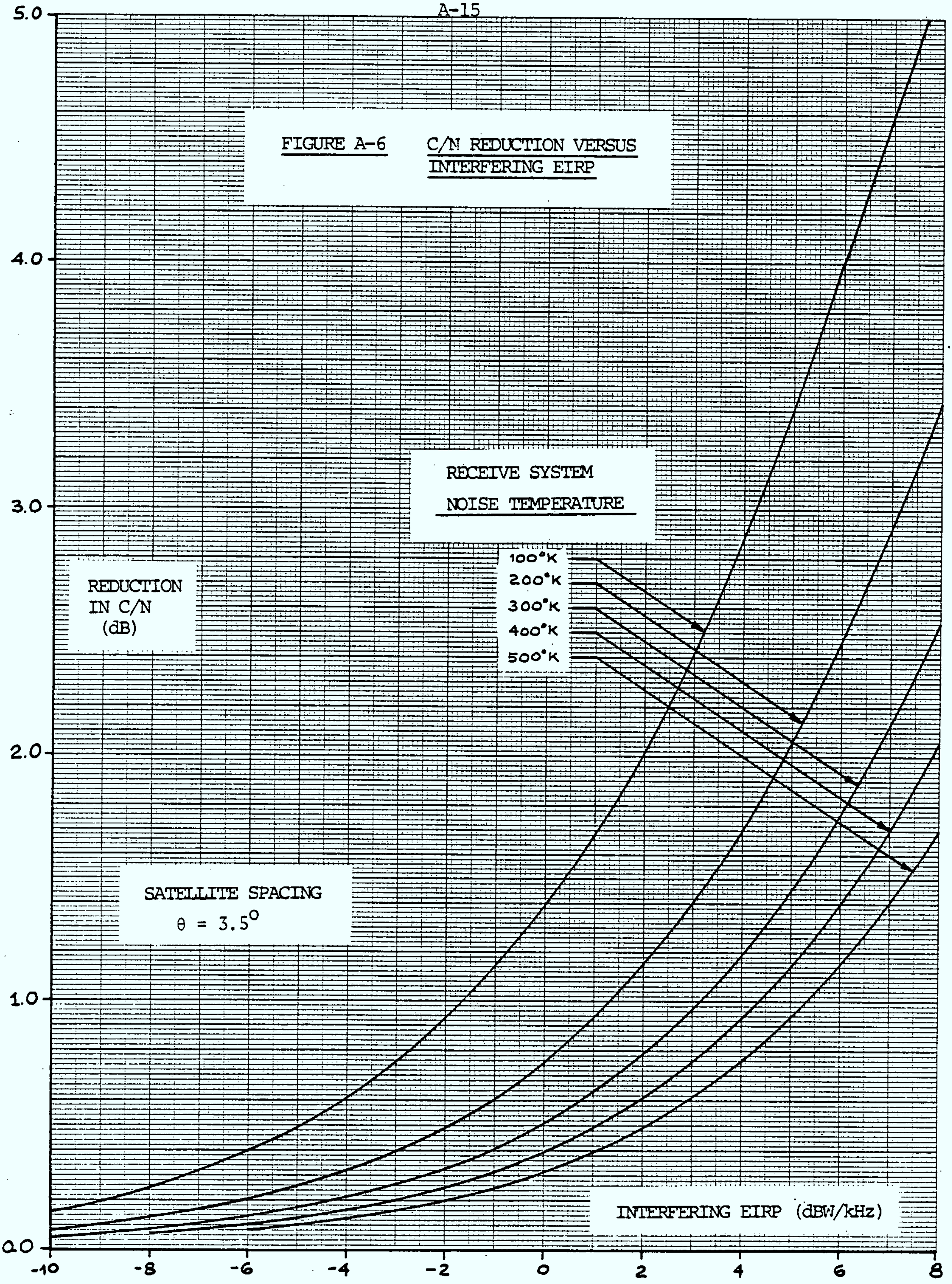

FIGURE A-6 C/N REDUCTION VERSUS INTERFERING EIRP

- 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 narrow-band interference, the interfering carrier bandwidth approaches the SCPC carrier bandwidth and the interference at the SCPC demodulator input is neither white nor gaussian. A detailed treatment of narrow-band interference on FM/SCPC and Δ-mod/CPSK/SCPC is contained in [1]. However, a digital SCPC system is generally less sensitive than an FM/SCPC system to narrow-band interference for the following reasons:

(a) The effects of interference* can be completely compensated for by an increase in the carrier-to-thermal noise ratio.

(b) Unlike FM, no subjective degradation due to baseband tones or intelligible crosstalk will occur.

For our purposes, non-stationary interference is defined as interference which produces variations in performance at the output of the SCPC demodulator. If the variation is sufficiently rapid as to be imperceptible to the ear, the average level of baseband interference can be considered as an objective for voice transmission. For voice-band data transmission, the ensemble of interference statistics and the combined effect on bit error rate should be estimated. This analysis is normally circumvented by designing to the maximum

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*RF interference in a digital transmission system is not demodulated directly into baseband interference, but rather increases the bit error rate (BER) and the corresponding level of bit error noise.

level of interference. When the interference varies at a perceptible rate, it is not obvious what the subjective effects will be or what design procedure should be adopted. Designing the system to meet overall noise objectives under worst-case interference conditions normally ensures satisfactory performance.

Because they are relatively narrow-band and low power, both FM and digital SCPC carriers are vulnerable to various types of non-stationary interference that could be generated in an adjacent 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 burst repetition frequency.

(5) Swept frequency carrier generated by link analyzer.

All of these processes vary at a rate less than the bandwidth of the SCPC carrier and, therefore, produce transient or time-varying effects not predicted by quasi-stationary analysis. The average carrier-to-interference ratio can be high but the degradation severe!

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*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.

APPENDIX B

FADE MARGIN REQUIREMENTS

For a large-scale, operational rural satellite communications network, it must be ensured that link performance does not fall below a specified threshold (which demarcates just acceptable from acceptable performance) for some high percentage of time, typically 99.9%.

To ensure this link availability, the traditional approach has been to allocate fade margins to threshold to offset degradations in operational carrier-to-noise ratios caused by such factors as attenuation and depolarization due to rainfall; antenna pointing errors due to satellite drift and wind loading; ice and snow accumulation; tropospheric/ionospheric scintillation (pre-dominant at very low elevation angles, especially in equatorial regions); equipment aging; etc.

Fade margins have previously been applied based on operational experience but in cases where limited experience has been available, margins have tended to be conservative. For the 12/14 GHz satellite communications band where the effects of fading, particularly due to rainfall, increase significantly, there is no operational experience to rely on.

Efforts have been made to devise theoretical and empirical models to predict fade statistics for line of sight propagation between an earth station and a satellite. A general approach for evaluating end-to-end link fade statistics due to all effects as a function of readily available climatological parameters and system parameters has been developed[1], but its accuracy is again limited by the underlying accuracy of the models assumed. The variability in the fading mechanisms for the earth

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[1] Bantin, C.C. and Lyons, R.G., "The Evaluation of Satellite Link Availability", IEEE Trans. on Communications, Vol. COM-26, June 1978, pp. 847-853.

station-satellite-earth station links for the various regions of Canada and the general lack of fade statistics complicates the situation.

Limited fade statistics gathered thus far for two locations in Ontario and Quebec through the Hermes satellite program indicate that for 0.01% of the year, fades greater than or equal to 10 dB could occur; for 0.1% of the year, 3 to 4 dB; for 0.5% of the year, approximately 2 dB. For the Atlantic Maritimes, fade depths are expected to be, on the average, slightly greater due to the intense and prolonged rainfall activity generally experienced whereas in the western and northern regions of the country, fade depths are expected to be lower than the values mentioned. For the far northern regions, the more dominant effect is the tropospheric scintillation encountered rather than rainfall.

The application of a large, fixed fade margin for all regions of Canada is therefore pessimistic to varying degrees and compounds the problem of inefficient use of the satellite transponder already inherent with the use of small aperture earth terminals. Higher fade margins require more earth station transmit EIRP or receive G/T, realized by increasing HPA size and/or antenna diameter (which must be limited to avoid the need for accurate pointing or tracking and possibily by the desire for rooftop assembly). Off-axis EIRP is also limited by tolerable interference levels into future adjacent 12/14 GHz satellite systems.

Clearly, the magnitude of the fade margin used has a considerable impact on earth and space segment costs and is a contentious issue which cannot be presently resolved. For the purposes of the link calculations, an end-to-end fade margin to threshold of 7 dB has been assumed. This can be apportioned as follows:

HPA Aging	0.5 dB
Ice/Snow Accumulation	0.5 dB

Climatological Conditions (0.1% of time*)	4.5 dB
Antenna Pointing Error (satellite drift, wind and ice loading)	1.5 dB
TOTAL	7.0 dB

This fade margin should be sufficient to provide an end-to-end link availability of equal to or better than 99.9% of the time. Possible techniques for reducing this fixed fade margin include the use of up-link power control and site diversity as discussed in Section 2.3.4.

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*For a backed-off, down-link noise dominated link, up-path and down-path fades add in dB or their probability density functions (pdf's) are convolved to produce a resultant fade pdf[2]. Unavailability is therefore approximately the sum of up-path and down-path unavailabilities, i.e., the quoted 99.9% fade margin really means say 99.94% up-link availability and 99.96% down-link availability.

[2] Lyons, R.G., "Combined Effects of Up-Link and Down-Link Fading Through a Power Limiting Satellite Transponder", IEEE Trans. on Communications, Vol. COM-22, March 1974, pp. 350-352.

APPENDIX C

EARTH STATION HPA COMBINING AND BACKOFF REQUIREMENTS

C.1 Introduction

This appendix examines earth station HPA backoff and combining requirements for two types of SCPC transmission, viz., FM/SCPC and PSK/SCPC. For single carrier transmission or multi-carrier operation of single HPA, combining is not a consideration. However, configurations which employ more than one active HPA may be attractive, and hence the following three methods of combining are compared:

1) Hybrid combining
2) Circulator combining
3) Diplexer combining

For the purposes of these discussions, only 4 carrier transmission has been considered but the techniques discussed should be general enough to allow for expansion of carrier capacity.

The selection of transmitter configuration(s) has significant impact on capital cost, maintainability, service availability, and power consumption of the terminal, and therefore constitutes an important aspect of the design.

C.2 Single Carrier Transmission

Since a band-limited FM carrier exhibits an essentially constant amplitude, it undergoes very little phase distortion or energy spreading due to amplifier non-linearities and thus the earth station HPA can be operated at saturation, i.e., 0 dB output backoff. However, a band-limited digitally phase modulated (PSK) SCPC carrier exhibits substantial amplitude modulation which increases as the symbol rate-to-channel bandwidth approaches the Nyquist limit.

When passed through the earth station high power amplifier (for example, a TWTA), which typically exhibits a non-linear input-output power transfer characteristic and AM-to-PM transfer, such a signal may be distorted and energy spread beyond the original frequency band[1]. The in-band distortion, resulting primarily from AM/PM conversion, degrades the bit error rate (BER) versus E_b/N_o performance of the link[2]. The spread energy, resulting mainly from amplitude clipping can constitute an important source of interference to adjacent SCPC carriers accessing the transponder.

Figure C-1 illustrates the spectrum spreading of a PSK carrier as a result of varying HPA backoff. Based on hardware simulations carried out for the European Space Agency's (ESA) Orbital Test Satellite System, it was concluded that the optimum earth station HPA output backoff was approximately 3 dB[3] and is the value which has been assumed for the link calculations*.

Reduction of the output backoff towards saturation would result in the degradations mentioned above. Use of a bandpass filter at the output of the HPA to limit the spread energy would introduce further power loss thus necessitating an increase in HPA power in compensation. The net effect of reducing the output backoff is, therefore, quite minimal and is not considered further.

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[1] Lyons, R.G., "Effects of PSK Spectral Spreading in a Satellite Transponder", ICC-74, Minneapolis, pp. 36B-1, -6.

[2] Lombard, D., "PSK Transmission over Non-Linear Satellite Channels", ICC-74, Minneapolis.

[3] Colby, R.J., "The Implications of Using High-Power Travelling-Wave-Tube Amplifiers with Up-Link Power Control at OTS-Type Earth Stations", ESA Journal 1977, Vol. 1, No. 2, pp. 165-176.

* For fast FSK (FFSK) transmissions in an equivalent bandwidth, output backoff can be reduced to 2 dB or perhaps less.

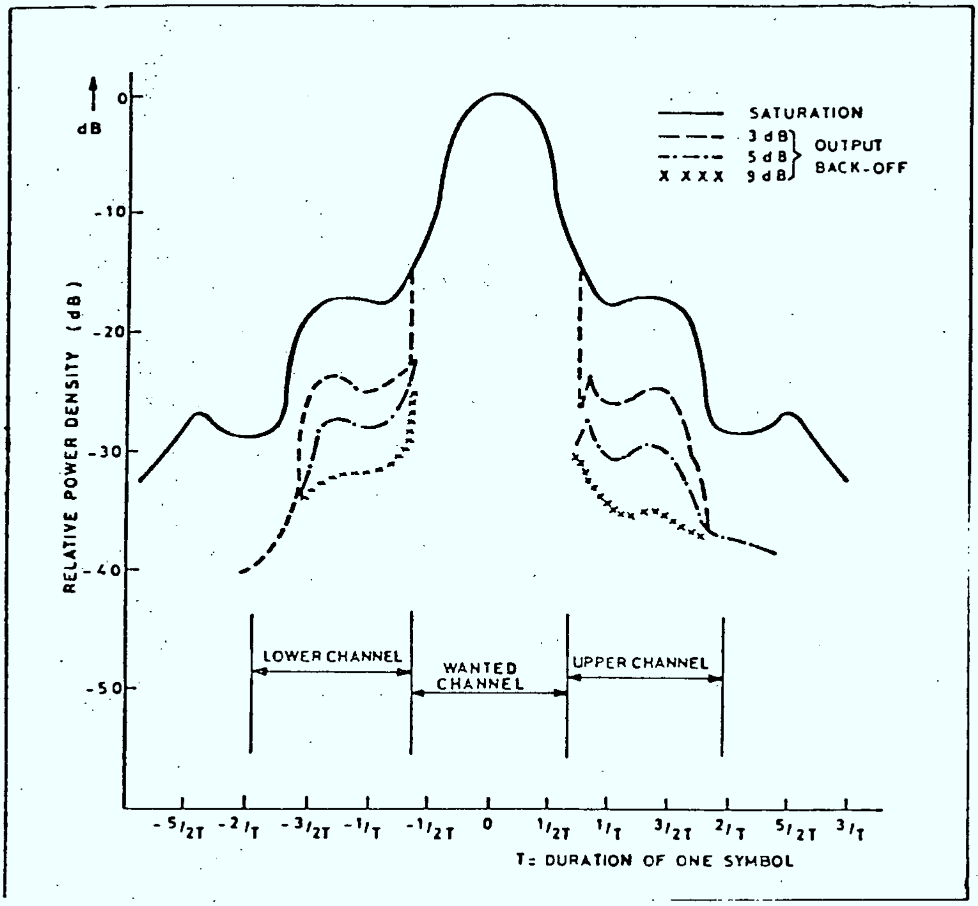

FIGURE C-1 - SPECTRUM SPREADING OF A PSK CARRIER CAUSED BY VARYING HPA BACKOFF

C.3 Multi-Carrier Transmission

For multi-carrier transmission through a Class C amplifier, the backoff required to reduce the level of intermodulation products generated is essentially the same for FM and PSK transmissions. In the FM case, however, intelligible crosstalk* may further limit backoff, especially if bandlimiting IF filters (subject to gain slope) are present in the transmit channel unit.

For N = 2 to 4 carriers, an output backoff per carrier of 5 + 10 log N is assumed. For more than 4 carriers this is increased to 6 + 10 log N. Note that with 2 carriers, operation at an output backoff of only 4.5 dB per carrier is possible, providing the large (out-of-band) 2A-B products are removed by a post-filter prior to up-link transmission to the satellite. The insertion loss of the filter must in fact be added to this figure for proper comparison. For arbitrary DAMA assignment of SCPC frequencies, however, no single output filter bandwidth is satisfactory. This mode of operation is nonetheless considered in the 2 + 2 configuration described in C.3.3.

C.3.1 Multi-Carrier, Single HPA Operation

This mode of operation (Figure C-2) is the simplest and requires no HPA combining. However, output backoff required for this configuration is the greatest and, depending on the number of carriers to be transmitted, this could mean a larger, more costly, and less reliable HPA. A further disadvantage is that failure of the HPA would render the earth

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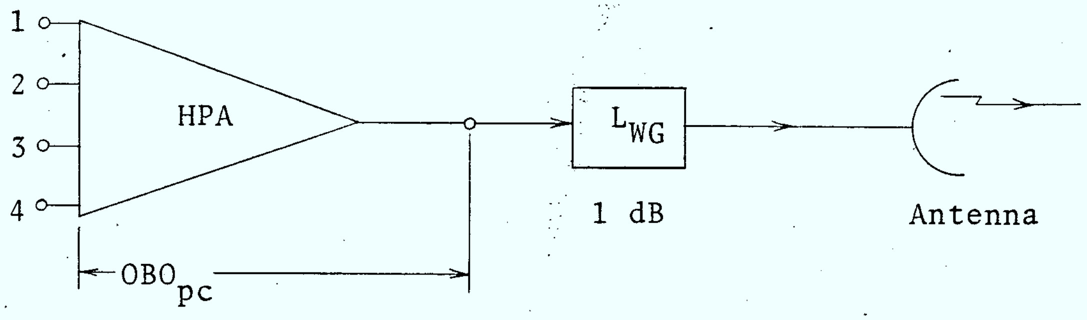
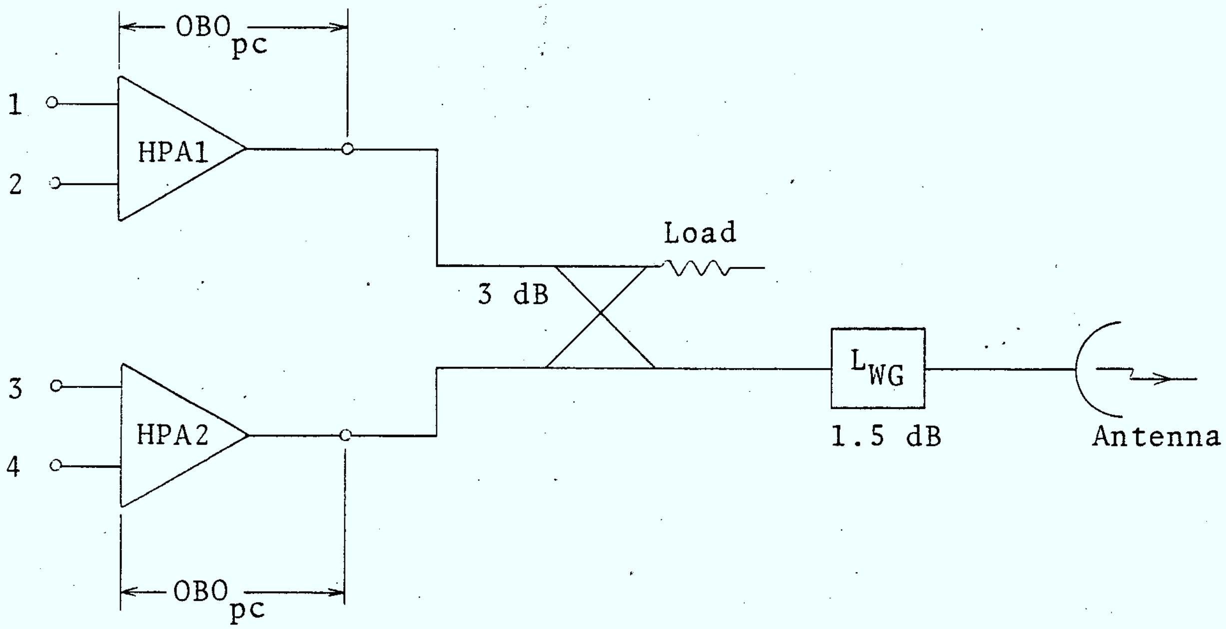
* Subjective measurements of intelligible crosstalk among a small number of companded FM SCPC carriers sharing a non-linear amplifier have not, to the author's knowledte, been made. Due to the narrow band nature of the SCPC carriers compared to the earth station transmit chain, intelligible crosstalk will certainly not be a problem if band limiting filters are not present following the FM modulators.



$$OBO_{pc} \cong 5 + 10 \log (4) = 11 \text{ dB}$$

FIGURE C-2 - MULTI-CARRIER, SINGLE HPA OPERATION



$$OBO_{pc} \cong 5 + 10 \log 2 \cong 8 \text{ dB}$$

Path Loss of HPA1 = Path Loss of HPA2 ≅ 4.5 dB

FIGURE C-3 - HYBRID COMBINING

NOTE: $OBO_{pc} \triangleq$ HPA output backoff per carrier, in dB

$L_{WG} \triangleq$ transmit waveguide losses, in dB station incapable of transmitting, i.e., the earth station availability would be critically dependent on the reliability of the HPA. A second redundant HPA in a 'hot' standby status with automatic or manual switchover in case of failure of the in-service HPA is probably required to ensure satisfactory service availability, further increasing cost. In summary, multi-carrier HPA operation has several undesirable features when the number of carriers is small (2 - 8).

C.3.2 Hybrid Combining

Hybrid combining is probably the simplest method of combining the output signals from two or more HPA's. The main drawback with this approach, however, is the large amount of transmitter power lost in the load.

Figure C-3 illustrates the method of combining the outputs of two HPA's, each transmitting two carriers, by means of a 3 dB hybrid. Note that the load termination must be capable of at least handling the saturated power capacity of either one of the HPA's.

With the parallel redundant configuration of the HPA's, failure of either one merely reduces the transmitter capacity, i.e., from four to two.

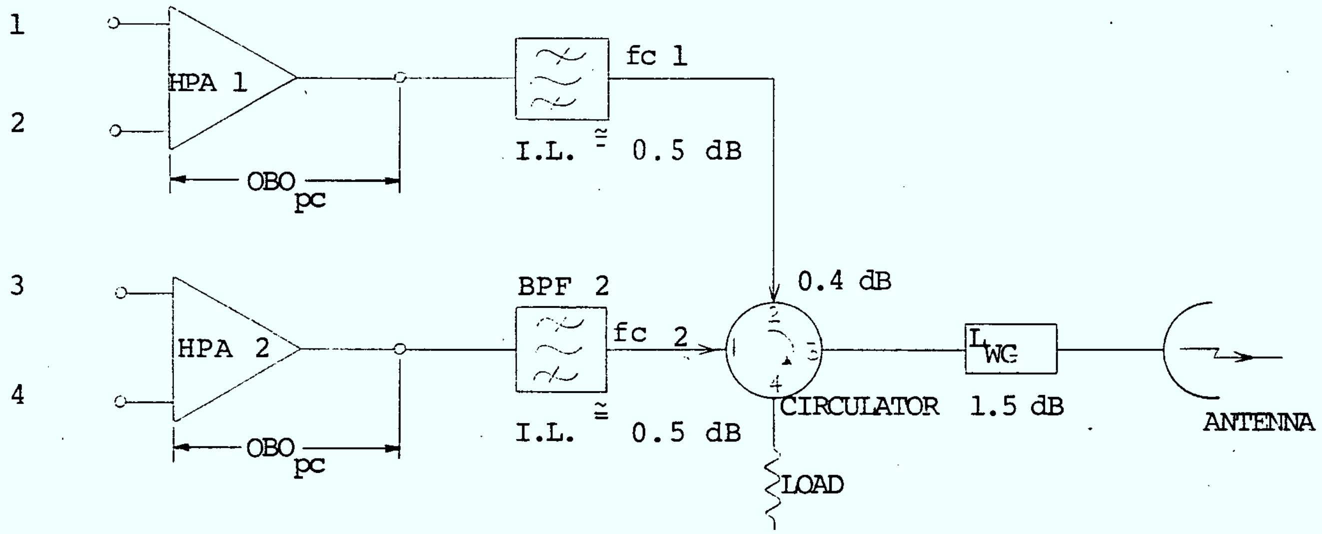
Expansion of SCPC carrier transmission capability up to say 8 carriers could be accommodated either by the addition of two up-converter + HPA chains (each handling 2 carriers) and hybrids with appropriate coupling factors or by up-grading the capacity of the present HPA's and operating with 4 carriers per HPA with appropriately increased output backoff per carrier (i.e., 11 dB instead of 8 dB). Note that with the latter approach, the power capacities of the hybrid combiner and load termination must be appropriately increased or allowed for at initial installation.

C.3.3 Circulator Combining

The circulator combining approach improves on the efficiency with which the two HPA outputs can be combined (as compared to the hybrid multiplexer) but places some limites on permissible carrier frequencies. This method of combining utilizes bandpass filters to both eliminate the 2A-B (and higher order) IM products and isolate the output frequency bands. This permits the HPA output backoff to be reduced by about 3.5 dB and also avoids the hybrid combining loss, giving a net reduction in HPA size in the order of 6 dB. General characteristics of the HPA output bandpass filters for four SCPC carrier transmission have been discussed in Section 2.3.1 with respect to frequency planning.

Referring to Figure C-4, the output of BPF1 centered on frequency, f_{c1}, enters the circulator at port No. 2 and exits at port No. 3 to the antenna. The loss experienced in the circulator will be approximately 0.4 dB or the insertion loss of the circulator. The output of BPF2 centered on frequency f_{c2} enters the circulator at port No. 1, exits at port No. 2, is reflected at BPF1, re-enters the circulator at port No. 2 then finally exits at port No. 3 to the antenna. Any stray reflected power from port No. 3 is absorbed in the load termination at port No. 4. Since powers are additive in the circulator, its power capacity should be sized appropriately to allow for possible expansion and HPA capacity upgrading.

Expansion up to 8 carrier capability can be accomplished either by upgrading (by 6.5 dB) the HPA capacities and operating with 4 carriers per HPA (with output backoff per carrier

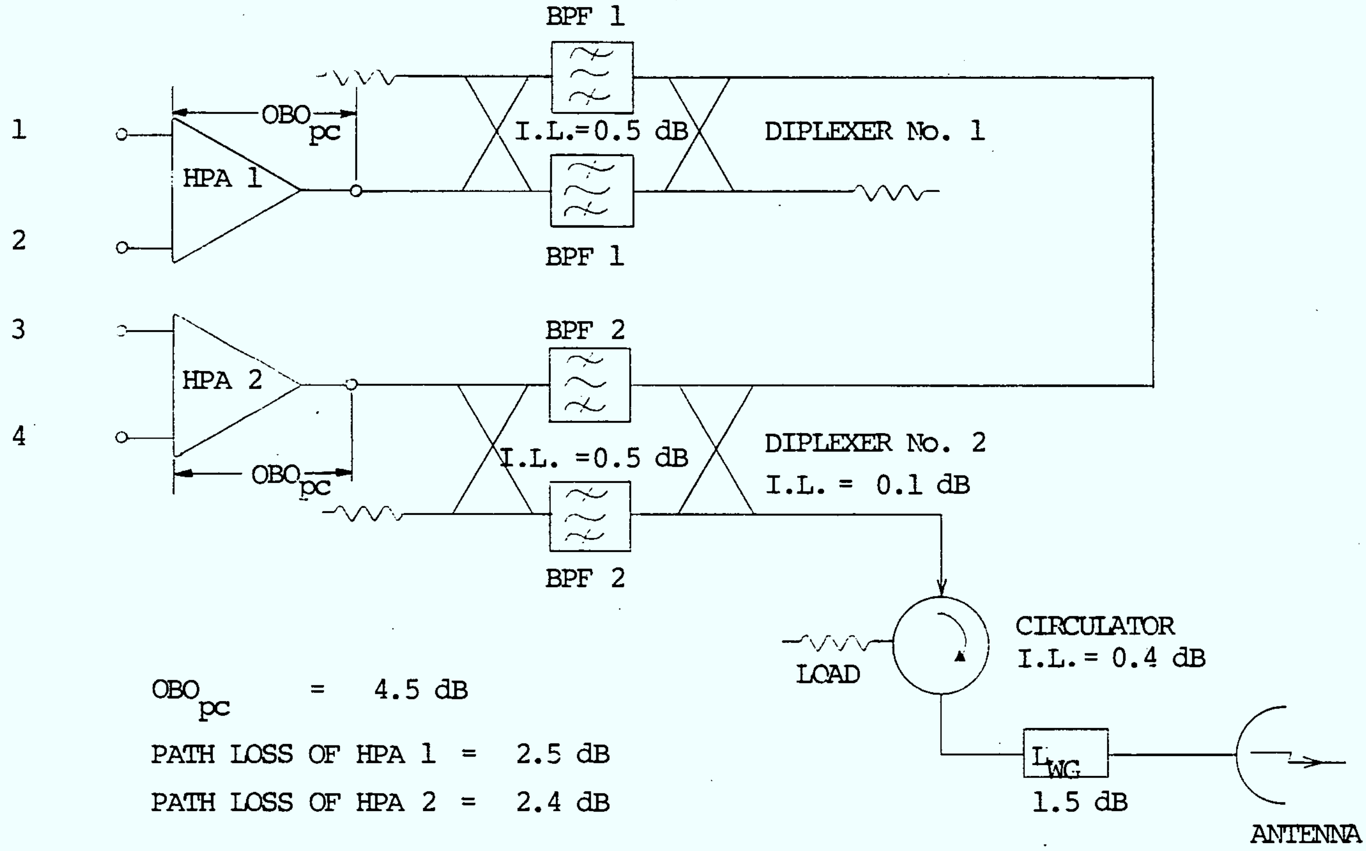


OBO$_{pc}$ = 4.5 dB

PATH LOSS for HPA 1 ≅ 2.4 dB

PATH LOSS FOR HPA 2 ≅ 2.8 dB

FIGURE C-4 - CIRCULATOR COMBINING



OBO$_{pc}$ = 4.5 dB

PATH LOSS OF HPA 1 = 2.5 dB

PATH LOSS OF HPA 2 = 2.4 dB

FIGURE C-5 - DIPLEXER COMBINING

of 11 dB) or by adding additional chains each consisting of u/c, HPA, bandpass filter and circulator, and operating with two carriers per HPA.

C.3.4 Diplexer Combining

The most efficient method of HPA combining is to use diplexers. Each diplexer uses two hybrids and two bandpass filters (Figure C-5) and acts essentially as a directional filter. The loss experienced by the output of diplexer No. 1 in passing through diplexer No. 2 is quite small (~ 0.1 dB). The loss experienced by carriers passing through the bandpass filters is approximately 0.5 dB.

This approach to combining is the most expensive and complex and is therefore not considered further.

Using the values of transmit EIRP per carrier for a 2-carrier level SCPC system listed in Table 4.5 (Section 4.1), the required HPA capacities for the transmitter arrangements in Figures C-2 to C-4 can be derived as function of antenna size (2-m and 3-m antennas considered). The results are summarized in Table C-1.

System	Transmit EIRP Per CXR	EARTH STATION HPA CAPACITY (WATTS)					
		Single HPA Antenna Size		Hybrid Combining Antenna Size		Circulator Comb. Antenna Size	
		2-m	3-m	2-m	3-m	2-m	3-m
32 kbps Δ	43.0 dBW	6.5	2.9	7.2	3.2	2.2	1.0
FM	43.9 dBW	7.9	3.6	8.9	4.0	2.7	1.2
FM-TED	42.1 dBW	5.3	2.3	5.9	2.6	1.8	0.8

TABLE C-1 - EARTH STATION HPA CAPACITY FOR 4-CARRIER TRANSMISSION - 2-CARRIER LEVEL SCPC SYSTEM

By assigning rough cost estimates for the various RF components (including antenna) in the multiplexing arrangements, an indication of the most economical multiplexing configuration can be obtained. It is assumed that for power levels less than or equal to 1 Watt, a solid state power amplifier will suffice; for levels less than or equal to 10 Watts, a 10 Watt TWTA. Further, only 32 kbps Δ and FM-TED will be considered.

The results of this rough cost comparison which apply both for 32 kbps Δ and FM-TED are as follows:

	Relative Antenna + HPA Cost For 4 Channels	
	2-meter	3-meter
1) Redundant HPA ('hot' Standby HPA and input/output Switching) - See Figure C-6	1.15*	1.21†
2) Hybrid Combining	1.10	1.15
3) Circulator Combining	1.21	1.00

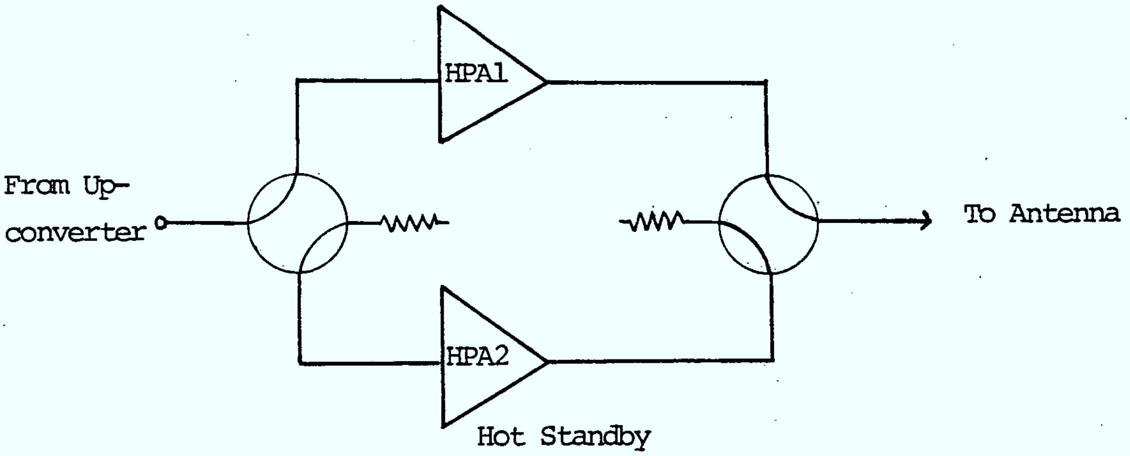


FIGURE C-6 - REDUNDANT HPA CONFIGURATION

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* Expandable to 6 circuits.

† Expandable to 8 circuits.

C.3.5 Summary and Conclusions

For single carrier SCPC transmission, HPA combining is obviously not required and HPA output backoff is somewhat dependent on the choice of RF modulation technique - FM, PSK or FFSK. For FM/SCPC, the HPA can be operated at saturation, i.e., 0 dB backoff; for PSK/SCPC, an HPA output backoff of 3 dB is required. A new contender which might offer advantages in a rural SCPC system is FFSK for which an output backoff of 1 to 2 dB would suffice. Some testing and analysis would be required to confirm an overall specification for an FFSK SCPC link, including selection of HPA backoff.

For multi-carrier SCPC transmission, four techniques have been considered viz., multi-carrier, single HPA operation; hybrid, circulator and diplexer combining with 2 carriers per HPA (2 + 2) operation. Diplexer combining has been eliminated from further consideration because of its complexity and cost. Using results presented in Section 4.1, the HPA capacity for the remaining multiplexing configurations has been derived.

For cost comparison purposes, a redundant HPA configuration for the multi-carrier, single HPA approach has been considered to ensure comparison on a nearly equal (reliability-wise) basis. Also presumed is a redundant up-convertor, as in the case of the 2 + 2 configurations. Rough cost estimates of the three configurations indicate that the circulator combining approach in tandem with a 3-meter antenna is potentially the most economical. However, since transmitter configuration impacts on the configuration of other earth station equipment, this approach may not necessarily lead to the lowest overall station cost. Reliability and circuit availability must also be considered (see Section 4.2). Further, this approach places certain restrictions on choice of SCPC carrier frequencies (see Section 2.3.1).

APPENDIX D

CYCLIC ASSIGNMENT MULTIPLE ACCESS: A NOVEL IMPLEMENTATION OF DEMAND ASSIGNMENT

D.1 Operation of Cyclic Assignment System

Consider the hypothetical system shown in Figure D-1. The Remote Terminals (A, B, C, D, etc.) communicate with each other via satellite in a single hop, full duplex, SCPC mode, with voice-activation. Channel assignment is as follows:

(1) Initially, all RT's have their transmitters and receivers set to Channel 1, active, but no carriers up. The Monitor and Control Terminal (MCT) receives on Channel 1, and transmits a "channel marker carrier" on Channel 2. (The marker carrier would be continuously modulated with some identification code.) It also continuously monitors all channels. See Figure D-2.

(2) Suppose A now wants to call B. After checking for incoming messages on Channel 1, A switches its receiver to Channel 2, and receives the MCT marker carrier. It then puts up a carrier on Channel 1 and requests authorization for entry from the MCT (transmits a code word). All other RT's receive and decode this message and interpret it as a "lock-out" until further notice (up to a specified period of time, which may be random or different for different terminals).

(3) The MCT decodes A's request for authorization and (if the system is not overloaded) responds by transmitting an authorization code and moving its marker carrier to Channel 4.

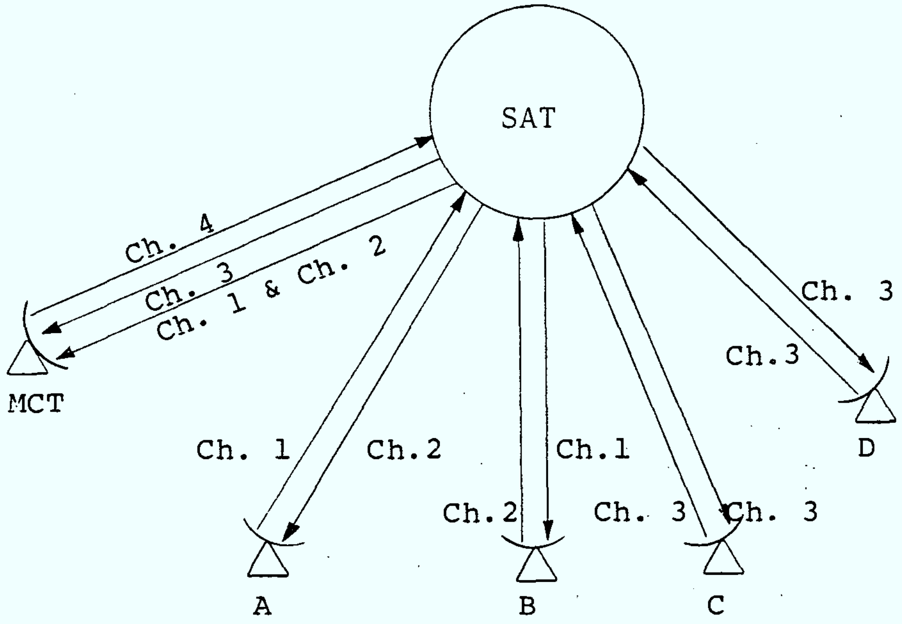


FIGURE D-1 SYSTEM

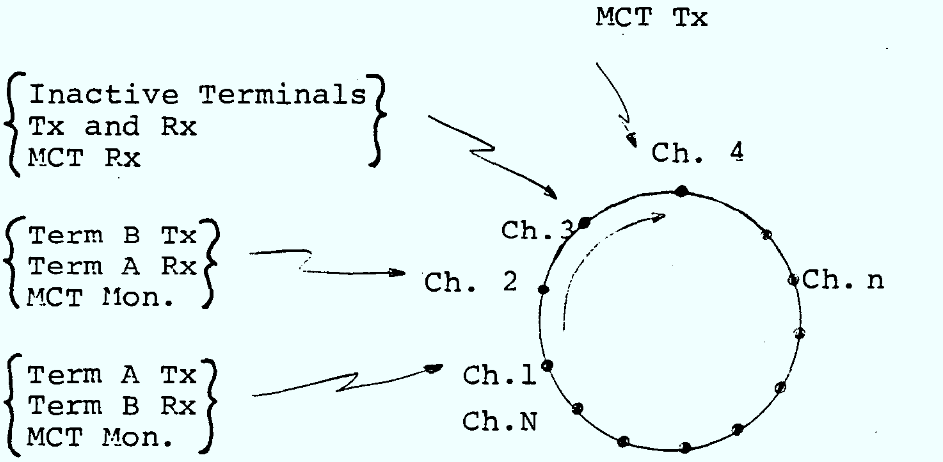


FIGURE D-2 ASSIGNMENT CYCLE

(4) Terminal A now puts up a carrier (Channel 1) and transmits the "address" code (telephone number) for B. All other terminals including the MCT receive and decode this message. Terminal B recognizes it as its own, retains Channel 1 receive, but selects Channel 2 transmit. At the same time, the MCT switches its receiver to Channel 2. Terminal B then puts up a carrier and transmits an "acknowledge" code, which only A and the MCT receive. The MCT now switches its receiver to Channel 3, but continues to monitor channels 1 and 2 so that system status will be known. All other RT's, having received and decoded A's calling message to B, recognize the code as not being their own, thereby being informed that Channel 1 and Channel 2 will now be engaged. Hence, they now step forward with transmitter and receiver until the MCT carrier is found (in this case, Channel 4), then backward one channel (to Channel 3). At this time, Channels 1 and 2 are assigned to A and B, all other RT's are standing by on Channel 3, and the MCT is monitoring Channels 1 and 2, receiving on Channel 3, and transmitting on Channel 4. This status is shown in Figures D-1 and D-2.

(5) Terminals A and B and Channels 1 and 2 are now effectively out of the assignment system until they hang up, and the above assignment procedure may thus be repeated until the cycle is completed.

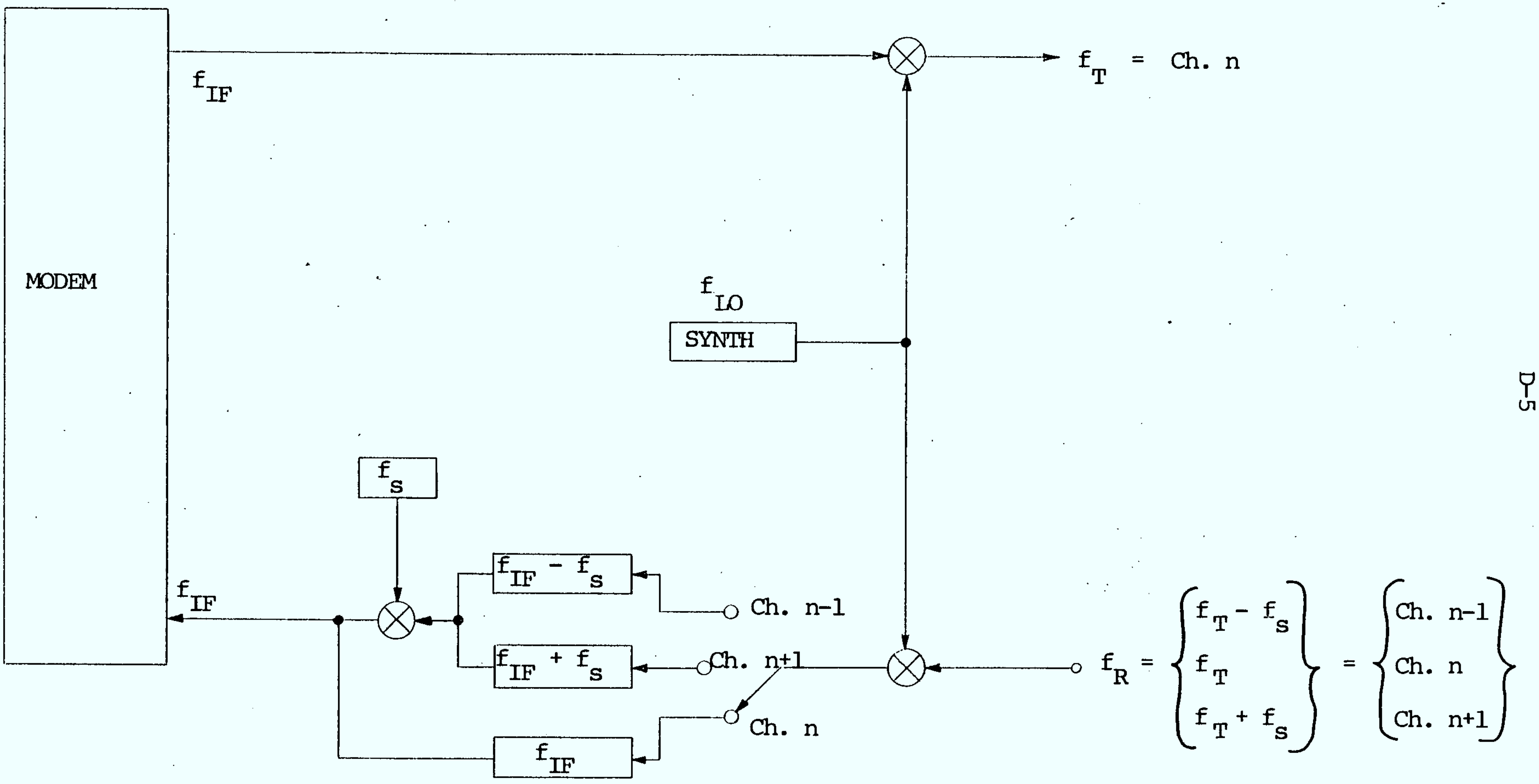
(6) When A and B hang up, they each transmit a "clear-down" code on their respective channels (1 and 2), which the MCT is monitoring, thus informing the MCT that Channels 1 and 2 are now disengaged. They then step forward until the marker carrier is found (in this case, Channel

4), then back one step (to Channel 3). Channels 1 and 2 are now simply abandoned until the assignment cycle is complete.

(7) Note that the MCT is able to maintain a record of the system status, since it receives request, set-up, acknowledge, and clear-down messages from the RT's. Also, if a destination RT is busy, there will be no "acknowledge" code returned, since it won't have received its number code. (It will be on a different channel.) If it is not busy, the "acknowledge" will be returned even if the called party does not answer. Hence, "busy" and "ringing" status can be inferred by the source RT.

(8) If the assignment cycle is complete before the first call (A to B) is cleared down, then the MCT is aware that Channel 1 and Channel 2 are still engaged. Hence, on the second assignment cycle, it omits these two channels (and more if necessary) and stops at the first pair of unused channels. Remote Terminals wishing to re-enter the assignment system will likewise cycle until the channel marker carrier is found. In this way the system can be loaded to full capacity, at which time the MCT "camps on" the last pair of unused channels (transmit on last even channel and receive on last odd channel). The MCT simply refuses to authorize the entry of additional RT's, which thus infer an overload condition and generate a "busy tone" for the users.

(9) Since for an RT, the receiver will always be on the same channel as the transmitter, or one channel above or below, the configuration shown in Figure D-3 could



<u>NOTE:</u> f_s = Channel Separation

<u>FIGURE D-3</u> - <u>POSSIBLE RT CONFIGURATION</u>

possibly be used. Note that this configuration requires only one synthesizer. Similarly, the configuration shown in Figure D-4 could be used for the MCT.

(10) The call set-up procedure is illustrated in flow-chart form in Figures D-5, D-6 and D-7 for the source RT, destination RT, and MCT respectively. The required messages are tabulated in Table D.1.

(11) In Figure D-5, note the following:

i) "Lock-out" occurs whenever another RT transmits a "Request for Authorization" code, whether or not the phone is off-hook. This condition expires when the other assignment is completed, or "time-out" occurs, whichever is first.

ii) "Timing out" begins as soon as "lock-out" occurs. Thus, the source RT may be part-way through "time-out" when the phone is taken off-hook. After "time-out", the RT is no longer "locked out", so that by hanging up and trying again, "Request for Authorization" will be transmitted (unless in the mean-time another RT has succeeded in transmitting a "Request for Authorization", thus "locking-out" this RT again.)

iii) The MCT "authorizes" and "moves off" only if it has received a single, clearly decodable request. If two RT's come up at the same time, neither is authorized (and all others are "locked-out"). Both will get busy tones, and try again or abandon the call.

(12) Note that the above description is applicable to a relatively unsophisticated implementation, exclusing such embelishments or priority, pre-emption, etc. As such, it cannot be directly compared in terms of complexity to the more sophisticated existing systems.

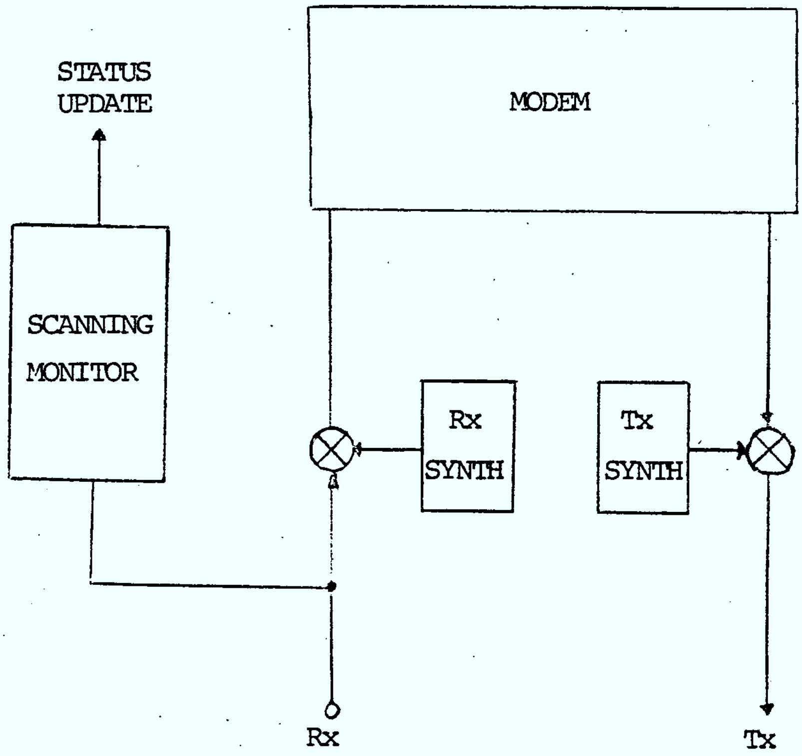


FIGURE D-4 - MCT CONFIGURATION

CALL SET-UP (SOURCE RT)

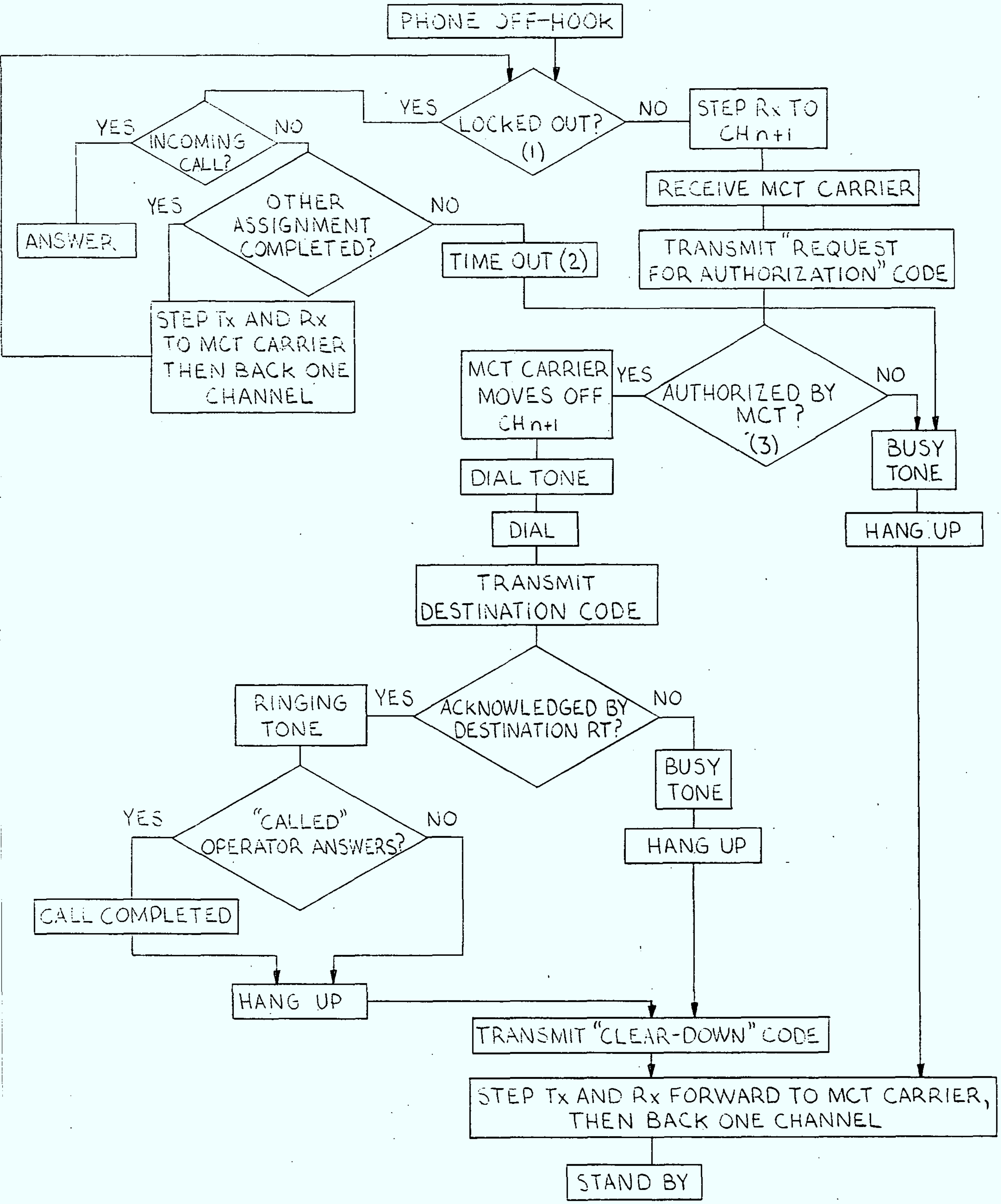


FIGURE D-5

CALL SET UP (DESTINATION RT)

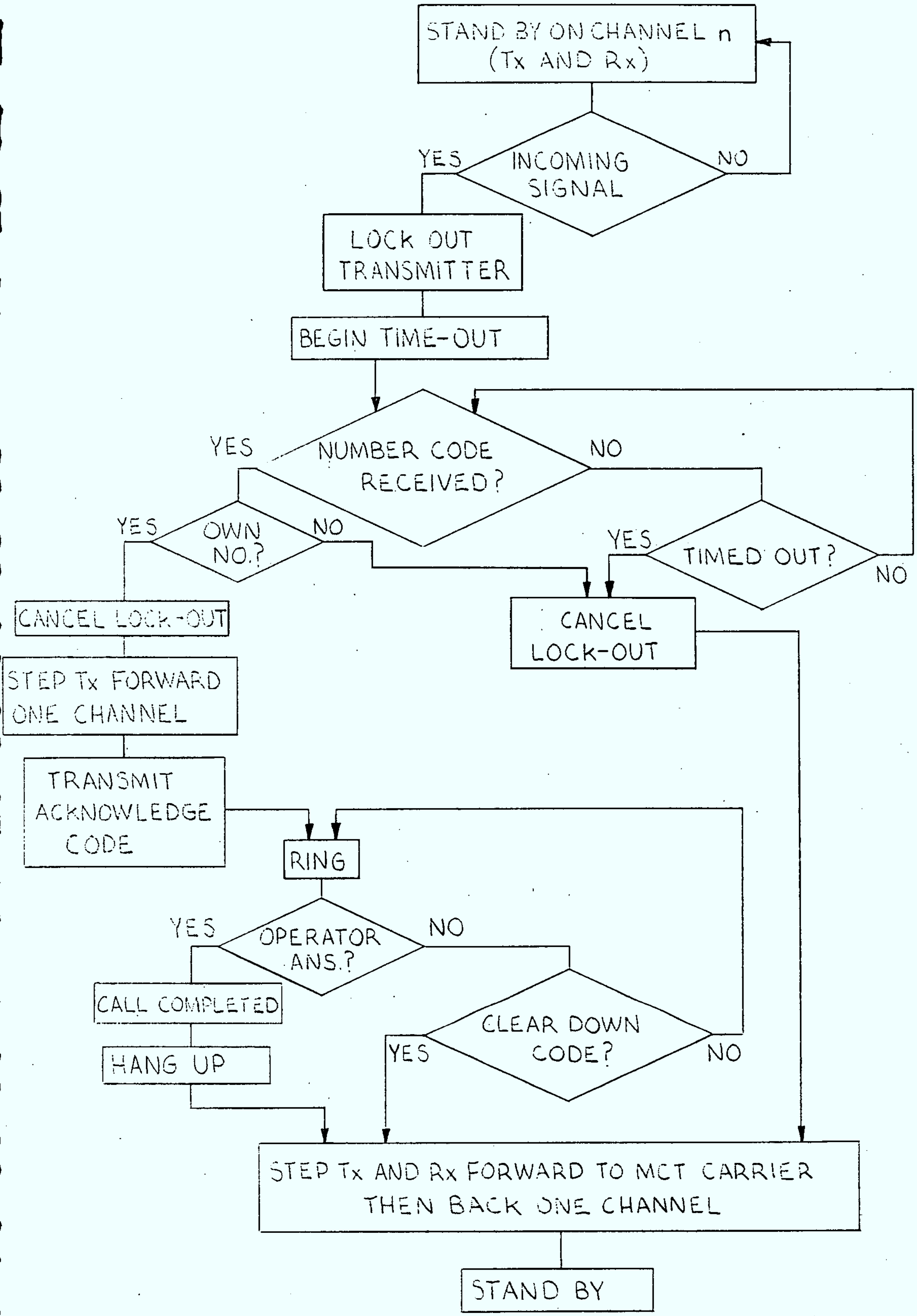


FIGURE D-6

CALL SET-UP (MCT)

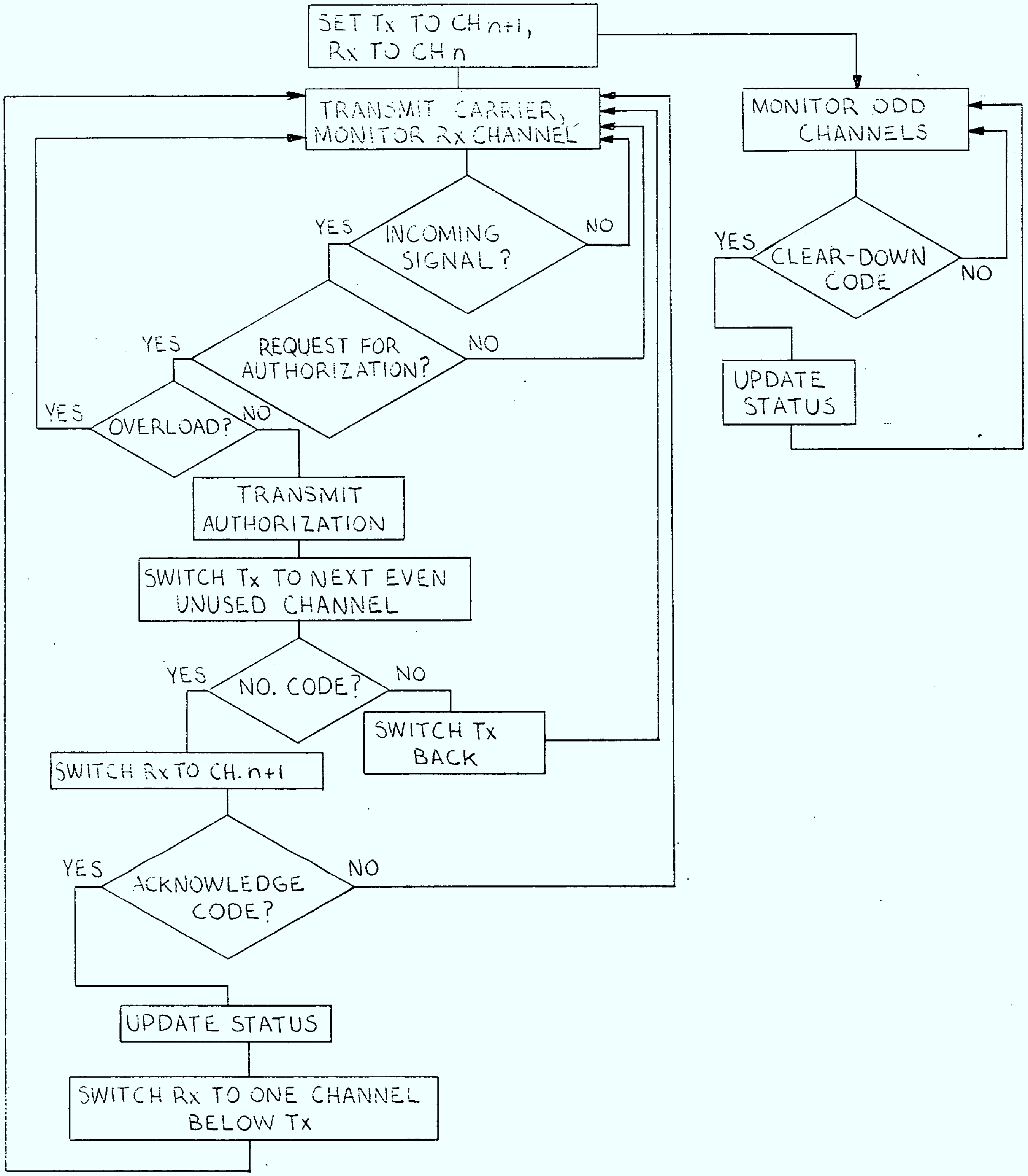


FIGURE D-7

	Message	From	Received By	Response
1.	Identification Code (Marker Carrier)	MCT	All RT's	Tx and Rx step back one channel.
2.	Request for Authorization	Source RT	All other RT's	Locks out transmitter.
			MCT	Authorizes if no overload, switches transmitter channel.
3.	Authorization Code	MCT	Source RT	Transmits address code.
4.	Address Code	Source RT	Destination RT	Transmits Acknowledge Code if not busy.
			All other RT's	Step forward to MCT carrier, then back one channel.
			MCT	Update Status. Rx step forward one channel.
5.	Acknowledge Code	Destination RT	Source RT	Ringing tone.
			MCT	Update Status. Rx step forward one channel.
6.	Clear-Down Code	Source RT and Destination RT	MCT	Update Status.

TABLE D.1 - MESSAGES

D.2 Some Additional Comments on Cyclic Assignment and DAMA

D.2.1 The clear-down procedure, involving the monitoring of all channels, is not essential to the basic concept. Alternatively, when an operator hangs up, his RT could step forward to the MCT carrier, then back one channel (to the MCT Rx frequency), and then transmit a clear-down code. However, this could lead to overlap of clear-down messages etc., with resulting inefficient utilization of the system under heavy loading.

Monitoring of all the assigned channels would also facilitate billing procedures, since identification of source and destination RT's could be contained in the clear-down messages. A scanning monitor could perhaps be used, since the clear-down code could be of quite long duration (e.g., up to several seconds). It should be noted that in the CRC system[1] all channels are also monitored, the clear-down messages being received via the assigned channels.

D.2.2 In a conventional DAMA system, fixed request and assignment channels introduce some vulnerability, since jamming or interference on either of these channels would yield the system inoperable. It has been proposed that the assignment and request channels be variable and that the RT's be equipped with an assignment-channel-seeking algorithm. This problem is circumvented without additional complexity in the Cyclic Assignment system, since the channel-seeking capability is inherent to its operation.

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[1] R. J. Campbell, CRC, "Hermes DAMA Experiment".

D.2.3 Some undesirable features of existing random access DAMA systems (e.g. CRC), which contribute to the grade of service, are:

(1) Request messages are rather long, containing such information as source code, destination code, etc., which must be correctly interpreted by the Central Control Station (CCS). Since the request channel is common to all users in a random access mode, there is a finite probability of "message overlap", even with light traffic. When this occurs, presumably both calls are lost, with no acknowledgement from the CCS.

(2) Even if overlap does not occur, occasionally requests will arrive more frequently than the CCS can process them, resulting in a request queue. (Several message transactions are required to complete an assignment.) Hence, incoming requests must be stored and handled sequentially, with the result that some users will have to wait some length of time before being serviced (or acknowledged). If storage is not adequate, some calls will be lost. Thus, a conventional DAMA system is potentially susceptible to "call frequency overload", as well as "traffic overload".

(3) When system overload is approached, request frequency will increase due to re-dialling of incompleted calls. Hence, message overlap and request queueing will be increased, ultimately resulting in a "call frequency overload" condition, and decreasing the overall capacity of the system. This undesirable mode of degradation can be overcome by utilizing assignment channel activity to "lock out" the transmitters of other RT's until the first assignment has been completed. A busy tone could be returned to the user if the request channel did not become available after some pre-determined length of time.

(4) A considerable amount of manipulation and message transaction via the CCS and Common Channel is required before an assignment can be completed with a high level of confidence. This impacts on the assignment time (and possibly the traffic capacity), and hence the grade of service. It should also be kept in mind that the probability of an assignment error is proportional to the amount of message transaction required.

D.2.4 The above points are discussed below as applicable to the proposed Cyclic Assignment system:

(1) The "request for authorization" message can be quite short, as no other information need be transmitted at this time. For example, it can simply be a "unique word", common to all RT's, and need only be long enough to ensure detection with a high probability (and a low probability of false alarm). Hence, message overlap is less likely than for the DAMA system which requires more message transaction via the Common Channel. When overlap does occur, other RT's are locked out for a predetermined length of time, and the two competing RT's return busy tones to their operators.

(2) Since a request from one RT locks out all others until the first one transmits a destination code, the request queuing problem does not exist at the MCT, and facility to store requests is not required. Other users are simply held off by lack of dial tone. If two or more then come up with requests simultaneously, they will receive busy tones. This should disperse the queue, which is not likely to re-form in conditions of light traffic. Similarly, a time-delay, locking out the transmitter and dial tone for a (staggered) length of time after hang-up (due to busy tone) would smooth the peaks in call-frequency, so that "call-frequency overload" should not occur (except perhaps in systems having a high call rate).

(3) The lock-out features discussed above will prevent the sudden increase in request-frequency due to redialling, so that grade-of-service degration will be inherently graceful as traffic overload is approached.

(4) All messages are direct from terminal to terminal, rather than being decoded and re-transmitted by the CCS. Also, channel assignment messages are not required, since all RT's know, prior to request, which channels are to be used. Intervention by the MCT is minimal, so that assignment times and message transactions will be decreased, resulting in less complexity, less probability of message error, and better (lower) grade of service.

It should be noted that many of the desirable features inherent to Cyclic Assignment could be integrated in DAMA, but would result in added complexity and cost.

APPENDIX E

FUNCTIONAL DESCRIPTION OF COMPUTER PROGRAM DEVELOPED BY MCS TO COMPUTE CAPACITY OR G/T REQUIREMENTS FOR A NON-HOMOGENEOUS SCPC SYSTEM*

E.1 Program Application

This program computes the capacity or G/T requirements for a non-homogeneous single channel per carrier (SCPC) satellite system. A mix of earth station G/T's and required C/N_o's is accommodated, with up-link power apportioned to each type of link in an optimum manner. The calculations may be done for the SCPC carriers assigned randomly or equally spaced over the available channel slots.

In computing a link noise budget, the following effects are considered:

- up-link thermal noise
- up-link interference (allocated)
- intermodulation noise due to common amplification in the satellite TWT .
- down-link thermal noise
- down-link interference (allocated)
- voice-activation (optional)

The program can determine transponder capacity (number of channels) or required earth station receive G/T and transmit EIRP for an SCPC system in which there may be different earth station sizes, fade margins, or required C/N_o's per

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[*] This program was developed by Miller Communications prior to the commencement of this study, and in no way was funded by the study. A listing of the program which is MCS proprietory information, is therefore not included with this description.

carrier. In particular, one of the following unknown system parameters is computed:

- the capacity on one type of link (i.e., for particular G/T, C/N_o combination) given the number of channels assigned to all other types of links.
- the total transponder capacity (number of SCPC carriers) for a given traffic model that assigns relative capacities to each type of link.
- the G/T required for a group of terminals in the SCPC system given the desired link capacities.

For a homogeneous system (i.e., equal carriers), the unknown parameter to be computed is necessarily the total transponder capacity or earth station G/T common to all terminals.

E.2 System Model

Each link in an SCPC FDMA satellite communications system must meet a specified fair weather C/N_o requirement determined by the desired SNR or bit error rate performance of the link. The required fair weather C/N_o equals the desired operating C/N_o plus an appropriate fade margin. This margin may vary for different links in the system (e.g., one margin for links to stations having elevation angles > 10°, a larger one for links to stations having elevations < 10°); hence there may be different fair weather C/N_o objectives even in SCPC systems designed to provide a single operating C/N_o. Furthermore, since the G/T's of the participating SCPC earth stations may be different there may, in general, be several transmitted carrier power levels.

To achieve the most economic system design, we wish to choose the carrier levels so that the required fair weather C/N_o on each link is just met. This leaves one additional parameter to be determined, either a link capacity (i.e., number of carriers into a specific G/T with a specified C/N_o) or a required G/T given the link capacities. The former corresponds to maximizing system capacity assuming fixed (i.e., existing) earth stations, the latter minimizes the G/T required to achieve a fixed circuit capacity.

The traffic model is conveniently described by the matrix in Figure E-1.

Fairweather C/N_o Objectives

Earth Station G/T's

$$\begin{array}{c|ccc} & c_1 & \cdots & c_n \\ \hline g_1 & k_{11} & \cdots & k_{1n} \\ \cdot & \cdot & & \\ \cdot & \cdot & & \\ \cdot & \cdot & & \\ g_m & k_{m1} & & k_{mn} \end{array}$$

Carrier Capacities

FIGURE E-1

$$\vec{g} = (g_1, \ldots, g_m)$$

and

$$\vec{c} = (c_1, \ldots, c_n)$$

are vectors whose components denote all distinct G/T's and desired C/N_o's in the SCPC system. k_{ij} is the total number of carriers transmitted to earth stations having a $G/T = g_i$ with a received fair weather $C/N_o = c_j$. All

$$K = \sum_{i=1}^{m} \sum_{j=1}^{n} k_{ij}$$

carriers in the system access the same transponder; the individual carrier frequencies are not given explicitly but are either assigned randomly or at equal intervals across the usable transponder bandwidth. In the former case, the intermodulation spectral density is assumed essentially constant across the total usable bandwidth; in the latter (worst) case, all the in-band IM products fall on wanted carriers. These two conditions effectively specify average and worst case performances in a demand assigned SCPC system in which no constraints are imposed on the assignment of carrier frequencies.

The program can effectively be applied to SCPC systems which utilize only a part of the transponder (i.e., share its power and bandwidth). However, IM product noise due to the presence of other carriers is not included in the IM calculations, and must be allocated as a down-link interference entry.

E.3 Theoretical Basis

Assuming the required link parameters and performance objectives are given, the following defines the computations required to simultaneously balance up-link powers and determine the unknown SCPC system capacity or G/T for a given multicarrier input backoff. A more detailed presentation of this analysis including also optimization of Carson's rule bandwidth for FM SCPC systems has been given by Weinberger and Kanehira.[1,2]

The matrix

$$\Delta = \begin{bmatrix} \Delta_{11} & \cdots & \Delta_{m1} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ \Delta_{1n} & & \Delta_{mn} \end{bmatrix}$$

represents relative up-link carrier powers for each G/T, C/N_o combination; i.e.,

Δ_{ij} = ratio (in dB) of power of a carrier into an earth station having a $G/T = g_i$ at a desired $C/N_o = c_j$ to that of a carrier into a $G/T = g_1$ at a desired $C/N_o = c_1$. $(\therefore \Delta_{11} = 1)$

Relative powers are used here because it will be assumed that the satellite input backoff given by

IBO = satellite I/P backoff

is fixed.

For a sufficiently large number of carriers, and certainly in realistic cases, the multi-carrier TWT input signal has gaussian first order statistics, and therefore

OBO = multi-carrier satellite O/P backoff

and

$\left[\frac{C}{I}\right]_{cc}$ = centre channel carrier-to-IM product interference power ratio for equal and equally spaced carriers

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[1] Weinberger, H.L., and Kanehira, E.M., "Single Channel per Carrier Satellite Repeater Channel Capacity", IEEE Trans. Aerosp. Electron. Syst., Vol. AES-11, September 1975, pp. 805-813.

[2] Weinberger, H.L., and Kanehira, E.M., "Single Channel per Carrier Repeater Capacity, Part 2", IEEE Trans. Aerosp. Electron. Syst., Vol. AES-13, March 1977, pp. 188-196.

are computable as unique deterministic functions of IBO and the single carrier tube transfer characteristics (amplitude and AM/PM).[3,4] These curves must be made available prior to executing the program.

E.3.1 Simultaneous Link Equations

Consider the actual C/N_o performance of an i,j link carrier:

$$\left[\frac{C}{N_o}\right]_{up} = [EIRP]_{up} - [FSL]_{up} + [G/T]_s + 228.6 - IBO + 10\log_{10}\left[\frac{\Delta_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} k_{ij}\,\Delta_{ij}}\right] \quad (1)$$

where

$[EIRP]_{up}$ = saturating EIRP from earth station

$[FSL]_{up}$ = up-link free space loss

$[G/T]_s$ = satellite input G/T

$$\left[\frac{C}{I_o}\right]_{IM} = \left[\frac{C}{I}\right]_{cc} + I + 10\log(W) \quad (2)$$

where

$\left[\frac{C}{I_o}\right]_{IM}$ = carrier to intermod noise density

$$W = \begin{cases}\text{channel spacing (if voice-activation is employed)}\\ \text{carrier noise bandwidth (if voice-activation is not employed)}\end{cases}$$

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[3] Lyons, R.G., "A Stochastic Analysis of Signal Sharing in a Bandpass Nonlinearity", IEEE Trans. Comm., Vol. COM-22, November 1974, pp. 1778-1788.

[4] Westcott, R.J., "Investigation of Multiple FM/FDM Carriers Through a Satellite TWT Operating Near to Saturation", Proc. IEE, Vol. 1/4, No. 6, June 1967.

and

I = change in (C/I_o) due to unequal carrier powers and possibly non-uniform spacing

$$= \begin{cases} 10 \log \left[\dfrac{\Delta_{ij} \, K}{\sum\limits_{i=1}^{m} \sum\limits_{j=1}^{n} k_{ij} \, \Delta_{ij}} \right] & \text{for equally spaced carriers} \\ \\ 10 \log \left[\dfrac{\Delta_{ij} \, M}{\sum\limits_{i=1}^{m} \sum\limits_{j=1}^{n} k_{ij} \, \Delta_{ij}} \right] - L & \text{for randomly spaced carriers} \end{cases}$$

with

M = number of available channels

L = ripple margin

= 1.5 dB typically

$$\left[\frac{C}{N_o}\right]_{down} = [EIRP]_{down} - [FSL]_{down} + [G/T]_i + 228.6$$

$$- OBO + 10 \log_{10} \left[\frac{\Delta_{ij}}{\sum\limits_{i=1}^{m} \sum\limits_{j=1}^{n} k_{ij} \, \Delta_{ij}} \right] \qquad (3)$$

and

$[EIRP]_{down}$ = saturated EIRP from satellite

$[FSL]_{down}$ = down-link free space loss

$[G/T]_i$ = earth station G/T

= g_i dB/°K

$\left[\frac{C}{I_o}\right]_{up}$ = up-link carrier-to-up-link interference noise density

$$= \left[\frac{C_{saturated}}{I_o}\right]_{up} - IBO + 10 \log_{10} \left[\frac{\Delta_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{n} k_{ij} \Delta_{ij}}\right] \quad (4)$$

$\left[\frac{C}{I_o}\right]_{down}$ = down-link carrier-to-down-link interference noise density

$$= \left[\frac{C_{saturated}}{I_o}\right]_{down} - OBO + 10 \log_{10} \left[\frac{\Delta_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{n} k_{ij} \Delta_{ij}}\right] \quad (5)$$

In (4) and (5) $(C_{saturated}/I_o)_{up}$ and $(C_{saturated}/I_o)_{down}$ are the up and down-link to interference densities for a single carrier which saturates the transponder.

Then the received C/N_o is given by

$$r_{ij} = \left[\left[\frac{C}{N_o}\right]_{up}^{-1} + \left[\frac{C}{I_o}\right]_{IM}^{-1} + \left[\frac{C}{N_o}\right]_{down}^{-1} + \left[\frac{C}{I_o}\right]_{up}^{-1} + \left[\frac{C}{I_o}\right]_{down}^{-1}\right]^{-1} \quad (6)$$

defining a matrix $\vec{r}$ of received C/N_o's.

E.3.2 Statement of the Problem

Suppose there is one unknown parameter in the $\vec{g}$ and $\vec{k}$ matrices. Choose the $\vec{\Delta}$ matrix to optimize (maximum capacity or minimum G/T) the unknown parameter while meeting the C/N_o objectives defined in the $\vec{c}$ matrix. This specifies optimum system design under the constraint of a fixed satellite back-off. Re-evaluating for successively chosen backoffs leads to an overall system optimization.

E.3.3 Iteration Procedure

Initial estimates for the unknown parameter and relative carrier powers ($\vec{\Delta}$ matrix) are made. Then C/N_o's on each of the mn possible links are computed using the equations presented in 4.1 (links on which there are no carriers are omitted).

Received C/N_o's are compared to required C/N_o's and the $\vec{\Delta}$ matrix and unknown parameter readjusted according to the following inverse interpolation rules:

(1) Adjusting the $\vec{\Delta}$ matrix

$$(\Delta_{ij})_{new} = (\Delta_{ij})_{old} \frac{c_j}{r_{ij}} \frac{r_{11}}{c_1} \tag{7}$$

balances the carrier powers to obtain a constant c_j/r_{ij} ratio. Adjusting the unknown parameter forces this ratio to 1.

(2) Adjusting the Unknown Parameter

Three cases may be considered

- an unknown link capacity - i.e., k_{ℓ_1,ℓ_2}, $1 \leq \ell_1 \leq m$, $1 \leq \ell_2 \leq n$, is variable.
- an unknown total capacity - i.e., the $\vec{m}$ matrix specifies a fixed set of relative capacities, but

$$K = \sum_{i=1}^{m} \sum_{j=1}^{n} k_{ij}$$

is variable.

- an unknown G/T - i.e., g_ℓ, $1 \leq \ell \leq m$ is variable.

Case 1

$$\left(k_{\ell 1,\ell 2}\right)_{new} = \left(k_{\ell 1,\ell 2}\right)_{old} + \left(1 - \frac{\Sigma\Sigma\, k_{ij}\, \Delta_{ij} \frac{c_j}{r_{ij}}}{\Sigma\Sigma\, k_{ij}\, \Delta_{ij}}\right) \left(\frac{r_{\ell 1,\ell 2}}{c_{\ell 2}}\right) \left(\frac{\Sigma\Sigma\, k_{ij}\, \Delta_{ij}}{\Delta_{\ell 1,\ell 2}}\right) \tag{8}$$

Case 2

$$(K)_{new} = (K)_{old} \left(\frac{\Sigma\Sigma\ k_{ij}\ \Delta_{ij}\ \frac{c_j}{r_{ij}}}{\Sigma\Sigma\ k_{ij}\ \Delta_{ij}} \right) \tag{9}$$

Case 3

$$(g_\ell)_{new} = (g_\ell)_{old} + 2 \left(\frac{\Sigma\Sigma\ k_{ij}\ \Delta_{ij}}{\Sigma\ k_j\ \Delta_{\ell j}} \right) \log_{10} \left(\frac{\Sigma\Sigma\ k_{ij}\ \Delta_{ij}\ \frac{c_j}{r_{ij}}}{\Sigma\Sigma\ k_{ij}\ \Delta_{ij}} \right) \tag{10}$$

(in dB, an empirical equation).

(3) Selection of Initial Estimates for Unknown Parameter

A reasonable selection improves the speed of convergence but is not critical. The program iterates from initially stored values

K_{old} = 50 carriers

G/T_{old} = 18 dB/°K

which are typically conservative.

E.3.4 Optimization of Satellite Backoff[1]

This is performed by running the program for several backoffs and selecting the one which gives maximum capacity or minimum required G/T. Experience indicates that backoff variation of less than ± 1 dB about the optimum has little effect on transponder utilization efficiency; hence running the program with 1 dB backoff steps is normally adequate.

E.3.5 Bandwidth Limitation

Of course, if the transponder capacity computed according to the link equations (based on power requirements only) presented here exceeds the available number of channels, the system becomes band-limited and excess C/N_O margin is available. The program checks to ensure the computed power-limited capacity does not exceed the bandwidth-limited capacity.

A FEASIBILITY STUDY OF A 12/14 GHz SCPC SATELLITE COMMUNICATIONS SYSTEM TO MEET TELEPHONY REQUIREMENTS IN RURAL AREAS : FINAL REPORT