NTIA REPORT 89-243

SPECTRUM-CONSERVATION TECHNIQUES FOR FIXED MICROWAVE SYSTEMS

ROBERT L. HINKLE
ANDREW FARRAR

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

Alfred C. Sikes, Assistant Secretary
for Communications and Information

MAY 1989

ABSTRACT

Since the spectrum is a limited natural resource, the spectrum management community has a major interest in identifying spectrum conservation techniques that will provide more efficient spectrum utilization. Advances in new technology for fixed microwave systems in antennas, modulation schemes and signal processing techniques offer increased efficiency in spectrum utilization. This report analyzes the spectrum conserving properties of the various new technologies for fixed microwave systems applying the concepts in CCIR Report 662-2, and was defined as the spectrum conservation factor (SCF). The report concludes that the SCF technique is an effective indicator of the spectrum conserving properties of technologies which can be used to develop new spectrum standards.

KEYWORDS

Spectrum Efficiency
Spectrum Conservation Factor (SCF)
Fixed Microwave System
7125-8500 MHz Band

TABLE OF CONTENTS

Subsection **Page**

SECTION 1

INTRODUCTION

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

SECTION 3

ANALYSIS FOR SPECTRUM CONSERVATION TECHNIQUES

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

Table **Page**

LIST OF TABLES

TABLE OF CONTENTS
(Continued)

Figure **Page**

LIST OF FIGURES

LIST OF APPENDICES

Appendix

SECTION 1
INTRODUCTION

BACKGROUND

The National Telecommunications and Information Administration (NTIA) is responsible for managing the Federal Government's use of the radio frequency spectrum. NTIA's responsibilities include establishing policies concerning spectrum assignment, allocation and use, and providing the various departments and agencies with guidance to ensure that their conduct of telecommunications activities is consistent with these policies.[1] In discharging these responsibilities, NTIA assesses spectrum utilization, identifies existing and/or potential compatibility problems among the telecommunications systems that belong to various departments and agencies, provides recommendations for resolving any compatibility conflicts that may exist in the use of the frequency spectrum, and recommends changes to promote spectrum efficiency and improve spectrum management procedures.

The radio spectrum is a limited natural resource that must be carefully managed to ensure its availability to accommodate spectrum requirements for new telecommunication systems. Therefore, NTIA has established a long-range plan for management and use of the radio spectrum.[2] One of NTIA's major policy initiatives outlined in the plan is the establishment of procedures to ensure the efficient and effective use of the spectrum. However, because of the economic burden that can be associated with requirements for spectrum efficient communication techniques, NTIA adopts regulatory controls only where necessary to ensure the continued availability of the spectrum. This encourages effective and economical use of the spectrum, development of new technologies in a less restrictive regulatory environment, and the

---

1 NTIA, Manual of Regulations and Procedures for Federal Radio Frequency Management, National Telecommunications and Information Administration, Washington, D.C., Revised May 1988.

2 Long-Range Plan for Management and Use of the Radio Spectrum (U), U.S. Department of Commerce, National Telecommunications and Information Administration, Washington, D.C., May 1988.

application of new spectrum conserving technologies only where necessary. In order to accomplish this policy initiative, NTIA has begun:

1. the development of methods to identify heavily used geographical areas in a band,

2. the evaluation of available radiocommunication technologies with respect to their ability to conserve the spectrum.

These two elements will allow NTIA to identify heavily used geographical areas with sufficient lead-time to allow the identification and/or development of appropriate and economical spectrum conservation techniques so that a spectrum crises does not occur and regulatory and policy options are not limited.

Pursuant to element (1) above, NTIA has developed a method for identifying heavily used geographical areas in a band and indices for degree of band use.[3] With respect to spectrum conservation techniques, the Interdepartment Radio Advisory Committee (IRAC) has endorsed a study to identify spectrum conservation techniques for the Fixed Service.[4] This report specifically investigates those techniques applicable to fixed microwave systems.

---

3 Mayher, R.J.; Haines, R.H.; et al, The Sum Data Base: A New Measure of Spectrum Use, U.S. Department of Commerce, National Telecommunications and Information Administration, TR-88-236, Washington, D.C., August 1988.

4 MEMORANDUM TO: Deputy Associate Administrator, Office of Spectrum Management; FROM: Executive Secretary IRAC; SUBJECT: Spectrum Resource Assessment of the Federal Government Fixed Service Bands (Above 400 MHz,) NTIA Technical Memorandum 87-127, IRAC Doc. 25498/2.

OBJECTIVE

The objective of this task was to evaluate spectrum conservation techniques for fixed service point-to-point microwave systems to identify system-design considerations that promote more effective and efficient spectrum use.

APPROACH

The following approach was taken to accomplish the above objective.

1. Identify major fixed microwave system design factors that conserve spectrum (e.g., antennas, modulation, signal processing, transmitter output device, and RF filters) and the available technology options within each of the major design factors.

2. Establish a microwave reference system to permit the determination of representative systems parameters.

3. Develop a computer model to evaluate spectrum conservation techniques for the fixed microwave systems by applying the definition of spectrum utilization given in the International Radio Consultative Committee (CCIR) Report 662-2.[5]

4. Apply the computer model to determine which major design factors have the most impact on spectrum conservation and to rank available technology options within each of the major design factors.

---

[5] CCIR Report 662-2, "Definition of Spectrum Use and Efficiency," XVIth Plenary Assembly, Vol. 1, Dubrovnik, 1986.

GENERAL CONCLUSIONS

The following are general conclusions resulting from the study.

1. The spectrum conservation factor (SCF) is a technical concept that can be used to quantitatively assess the spectrum conserving potential of new technologies and to develop new spectrum standards.

2. The spectrum conserving potential of a system is a function of several design factors all of which must be taken into consideration when evaluating the spectrum utilization efficiency of a system. That is one can not say that a system with a particular modulation is more spectrum conserving than a system with another modulation without considering all other design factors such as antennas, signal processing, RF filters, etc.

SPECIFIC CONCLUSIONS

The following are specific conclusions related to spectrum conservation for each of the major system design factors.

1. Antennas

Microwave system antenna characteristics (sidelobe/backlobe levels) have a significant effect on the denial area of a system. For the three types of antennas (dish, shrouded dish and conical horn reflector) considered in the investigation, the following were determined.

a. The relative improvement in spectrum conservation of the shrouded dish and conical horn reflector antennas over the standard dish antenna is a function of the system modulation. The spectrum conservation improvement is approximately 0 to 150 percent for shrouded dish and approximately 150 to 1500 percent for a conical horn reflector. The greatest improvement occurs for 256-QAM modulation.

b. Due to the somewhat higher sidelobe levels close to the mainbeam, less than 20 degrees off-axis, for shrouded dish type antennas, there is no appreciable improvement in spectrum conservation for some modulations. However, the low backlobe level characteristics of shrouded dish antennas enhance the accommodation of systems in crowded cosite conditions.

2. Modulation

The choice of modulation type used in a microwave system has an effect on the spectrum (occupied bandwidth) and spatial area denied to other users. For the nine types of modulations considered in this investigation, the following were determined.

a. Single sideband (FDM/SSB) modulation, from a spectrum conserving point of view, is more efficient than the other modulations considered in the analysis for all antenna types.

b. The higher order digital modulations (modulations with higher transmission efficiency, bits/s/Hz) require higher transmitter output power levels. Therefore, when the CCIR definition of spectrum use and efficiency which takes into consideration denied area is used, modulations which have higher transmission efficiency (bits/s/Hz) may not necessarily be more spectrum conserving. Thus the transmission efficiency (bits/s/Hz) of the digital modulation may not suffice as an indicator of spectrum conservation.

c. For equivalent systems, with identical signal processing techniques, 64-QAM (Quadrature Amplitude Modulation) is more spectrum conserving (i.e., higher SCF value) than 256-QAM for all antenna types considered.

3. Signal Processing

Microwave system signal processing techniques can be used to improve the spectrum conserving properties of a system. For a microwave system using 64-QAM, the following were determined for the digital signal processing techniques considered in the analysis .

a. The improvement in spectrum conservation due to signal processing techniques is a function of the system antenna type. Microwave systems with dish type antennas obtain the greatest improvement in spectrum conservation when signal processing is used, with the improvement decreasing for systems with shrouded dish and conical horn reflector antennas respectively.

b. Because of the trade-off between system bandwidth and required carrier-to-noise ratio in error correction/coding techniques, high-efficiency coding techniques (i.e., coding techniques with high coding rates and coding gain) must be used to obtain an improvement in spectrum conservation.

c. The use of adaptive equalizers can improve the spectrum conservation properties of a system from approximately 25 to 90 percent depending on the type of antenna used.

d. Some microwave systems use both adaptive equalizers and error correction/coding techniques to improve system performance. The use of both signal processing techniques can improve the spectrum conservation properties of a system from approximately 30 to 170 percent depending on the type of antenna used.

4. RF Filters

The use of transmitter and receiver RF filters greatly enhance the spectrum conserving properties of microwave systems. Their application reduces intermodulation, adjacent channel and receiver spurious response interference.

RECOMMENDATIONS

The following are NTIA staff recommendations based on the findings of this report. NTIA management will evaluate these recommendations to determine if they can or should be implemented from a policy, regulatory, or procedural viewpoint. Any action to implement these recommendation will be via separate correspondence modifying established rules, regulations and procedures. The recommendations are as follows.

1. The NTIA in fulfillment of it's long-range planning objective of promoting more effective and efficient use of the spectrum, should initiate follow-on tasks to continue the investigation of spectrum conservation techniques for other services.

2. In geographical areas where bands are heavily used, the SCF concept should be for use in the development of spectrum standards which will promote more efficient use of the spectrum.

SECTION 3
ANALYSIS OF SPECTRUM CONSERVATION TECHNIQUES

INTRODUCTION

This section contains a discussion of the analytical approach used to evaluate spectrum conservation techniques for fixed point-to-point microwave systems. A reference system was used to determine nominal system parameters for the various design factors such as antenna, modulation, signal processing, transmitter output device and RF filters. These nominal system parameters are then used to evaluate the spectrum conservation trade-offs for the various design factors. The relative spectrum utilization efficiency for the various design factors are analyzed as well as the relative spectrum utilization efficiency of the state-of-the-art technologies within each of the major design factors.

The analysis is based on characteristics of microwave systems deployed in the government fixed service band of 7125-8500 MHz. However, the analysis was extended to consider the technology deployed in other point-to-point microwave fixed service bands and current state-of-the-art technology being developed.

ANALYSIS APPROACH

To assess the efficiency of the various design factors and technology options, it is necessary to have a quantitative measure of the relative spectrum conservation enhancement properties of that technology. In the past, analysis of spectrum efficiency has dealt primarily with RF bandwidth, transmission efficiency (Bits/second/Hz) or capacity efficiency (Voice channels/Hz).

To utilize the spectrum efficiently, any radiated energy should be kept to a minimum consistent with ensuring an adequate grade of service. This minimization should be effective in the time, frequency, and spacial domains. CCIR Report 662-2 defines spectrum efficiency as the ratio of communications achieved to the spectrum-space used. Spectrum-space is defined as the product of time, bandwidth, and the spatial volume denied to other users due to potential interference. For this study on analysis of spectrum conservation techniques for the fixed point-to-point systems, the equation in CCIR Report 662-2 was defined as the spectrum conservation factor (SCF) and is given as:

$$SCF = \frac{VC}{T*A*B} \quad (3\text{-}1)$$

where:

VC = Number of voice channels.
T = Fraction of time a system is used. Defined to be equal to 1 for this analysis.
A = Denial area (km^2)
B = Receiver System Bandwidth (MHz)

The above equation was chosen because it takes into consideration both spectrum and spatial (area) denial in assessing the spectrum conservation enhancement properties of a system. The denial area is the area in which another system can not operate without degradation in system performance below a specified performance criteria. The denial area is a function of the microwave system antenna pattern characteristics, transmitter output power and interference threshold level. APPENDIX A contains a detailed description of the computer program used to evaluate Equation 3-1 and examples of program input and output data.

The relationship between spectrum and spacial (area) denial trade-offs for the various design factors addressed in this section are summarized in TABLE 3-1.

TABLE 3-1

SPECTRUM CONSERVATION DESIGN FACTORS

DESIGN FACTORS	TRADE-OFFS
Antenna	Space
Modulation	Spectrum-space
Signal Processing	Spectrum-space
Transmitter Output Device	Spectrum
RF Filters	Spectrum

The following is a discussion of the application of Equation 3-1 for the design factors listed in TABLE 3-1. Representative system parameters for each of the design factors and technology options within each of the design factors are identified, and the associated spectrum conservation enhancement properties are assessed.

MICROWAVE REFERENCE SYSTEM CHARACTERISTICS

In order to apply Equation 3-1 to point-to-point microwave systems, it is necessary to establish characteristics of a microwave reference system between two microwave sites. TABLE 3-2 shows the system parameters for sites Alpha and Beta used to calculate the required system gain (G_s). The system parameters used in TABLE 3-2 are nominal values considered to be representative of a typical microwave hop. The system gain of 103 dB calculated in TABLE 3-2 is representative of nominal system gains for microwave systems in the 7/8 GHz band. This value of system gain will be used to determine the required transmitter power used to evaluate the spectrum conservation enhancement for the various design factors which follow.

ANTENNAS

The antenna of a microwave system is a key system design factor in addressing spectrum conservation. One of the major radiocommunications system components contributing to denial area is the system antenna. In recent years, significant advances in the antenna-design areas of sidelobe/backlobe reduction and polarization discrimination have provided the capability for enhanced spectrum efficiency in fixed microwave systems. Frequency re-use can be achieved by implementing antenna-design spectrum-conservation techniques. For example, antenna polarization discrimination is an effective and efficient means to double the channel capacity of a fixed point-to-point microwave system.

Antenna Pattern Characteristics

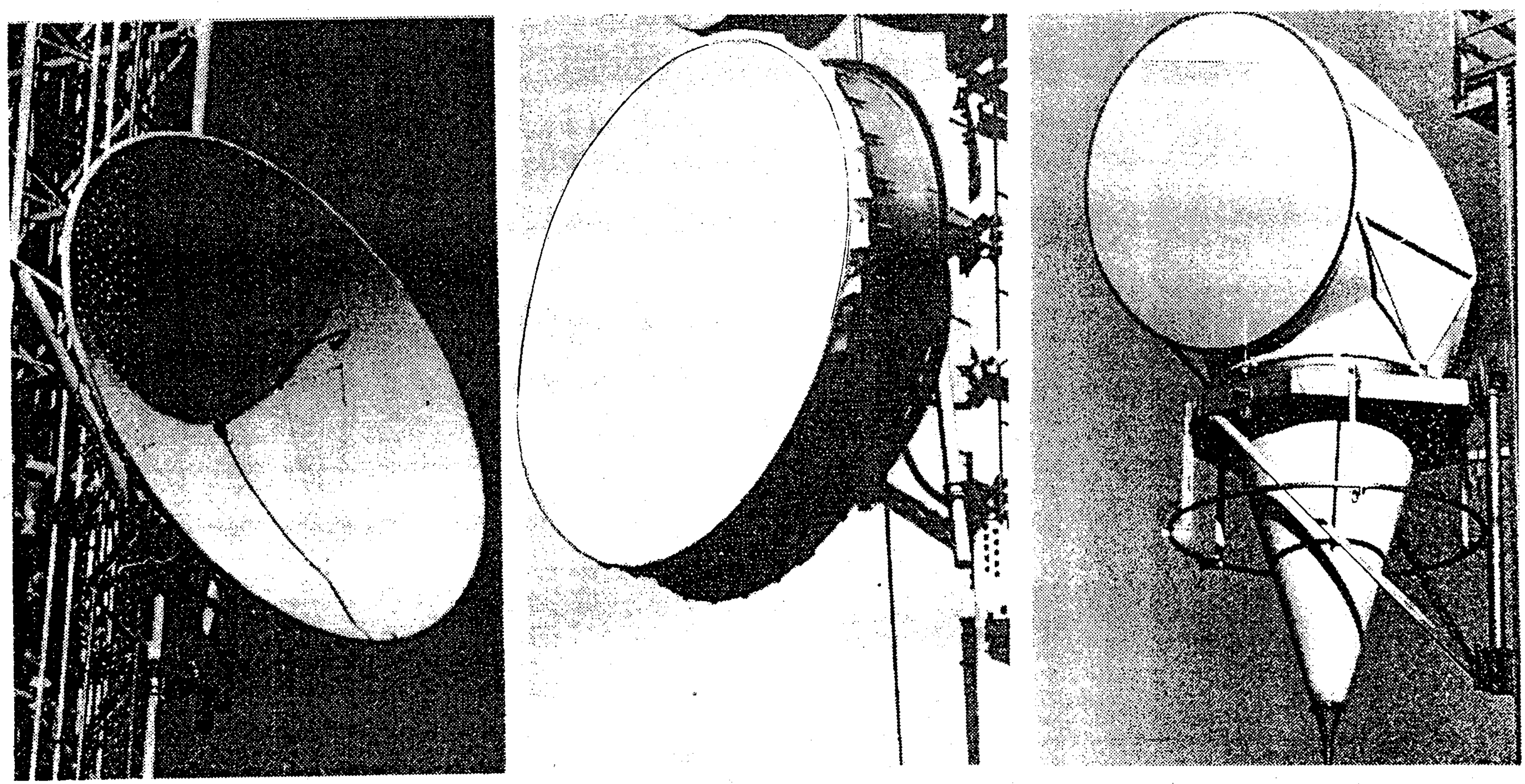
Spatial denial can be minimized if antenna pattern sidelobe/backlobe levels are minimized. The antenna radiation patterns, and therefore sidelobe distributions, vary with antenna type. For this analysis an eight foot antenna, approximately 43 dBi gain, has been used. Three antenna types (see Figure 3-1) commonly used in point-to-point microwave transmission are:

1. Standard Dish (STD)
2. Shrouded Dish, (SHD)
3. Conical Horn Reflector (CHR)

TABLE 3-2

HYPOTHETICAL HOP CHARACTERISTICS

FREQUENCY (MHz)		8000.0	
PATH LENGTH (kMS)		50.0	
SITE	ALPHA		BETA
SITE ELEVATION (METERS)	125.0		250.0
ANTENNA HEIGHT (METERS)	50.0		50.0
PATH ATTENUATION (dB)		142.0	
WAVEGUIDE LOSS (dB)	2.5		2.5
CONNECTOR LOSS (dB)	0.5		0.5
RADOME LOSS (dB)	0.5		0.5
TOTAL FIXED LOSSES (dB)	3.5		3.5
TOTAL LOSSES (dB)		149.0	
ANTENNA GAIN (dB)	43.0		43.0
TOTAL GAIN (dB)		86.0	
NET PATH LOSS (NPL) dB		- 63.0	
RECEIVER NOISE FIGURE (dB)	7.0		7.0
THEORETICAL RF C/N RATIO (dB)		SEE TABLES 3-3 & 3-4	
PRACTICAL THRESHOLD (C[MIN]) (dBm)		SEE TABLES 3-3 & 3-4	
FADE MARGIN (FM) dB		40.0	
SYSTEM GAIN (GS) dB [FM - NPL]		103.0	
TRANSMITTER POWER P(t) dBm		SEE TABLES 3-3 & 3-4	



STANDARD DISH (STD) SHROUDED DISH (SHD) CONICAL HORN REFLECTOR (CHR)

Figure 3-1. Fixed microwave system antenna types.

Standard parabolic dish (STD) antennas have unshielded reflectors and have a relatively low front-to-back ratio. Because of this, the radiation pattern characteristics of standard dish antennas produce larger denial areas than those for the two other types of antennas. A typical radiation pattern for a standard dish antenna with a 43 dBi gain is shown in Figure 3-2. Note that the backlobe levels for these antennas are only 55 dB down from the main beam. Despite this shortcoming, in many applications where frequency congestion is not serious and interference is less restrictive, these antennas may be used more economically.

The shrouded dish (SHD) type antennas are similar to the standard parabolic dish type antennas, except that they include a cylindrical built-out shield or shroud which improves the front-to-back ratio and wide angle radiation discrimination. A shrouded antenna typically has a front-to-back ratio of approximately 70 dB. The SHD type antennas are used in areas where frequency plans and operational coordination require the suppression of relatively high levels of side and backlobe radiation. A typical radiation pattern for a shrouded dish antenna with a 43 dBi gain is shown in Figure 3-2. One inherent characteristic of the shrouded dish antenna is the higher sidelobes close in (less than 20^0) from the main lobe (See Figure 3-2).

Conical horn reflector (CHR) antennas offer high quality radiation characteristics. These horn reflector type antennas, are well suited for use in areas where frequency congestion is burdensome. The feed for a CHR antenna includes a metallic conical horn structure. The front-to-back ratio for this type of antenna is approximately 90 dB. A typical pattern for the 43 dBi horn reflector antenna is shown in Figure 3-2.

Spectrum Conservation Factor

A plot of the transmitter output power versus denial area for a receiver interference threshold of -101 dBm is shown in Figure 3-3 for the three types of antennas. Although, the mainbeam gain for all the antennas were the same, the results shown in Figure 3-3 indicate that the CHR antenna has less denial area than the other two types of antennas. Also the difference in denial area for the three types of

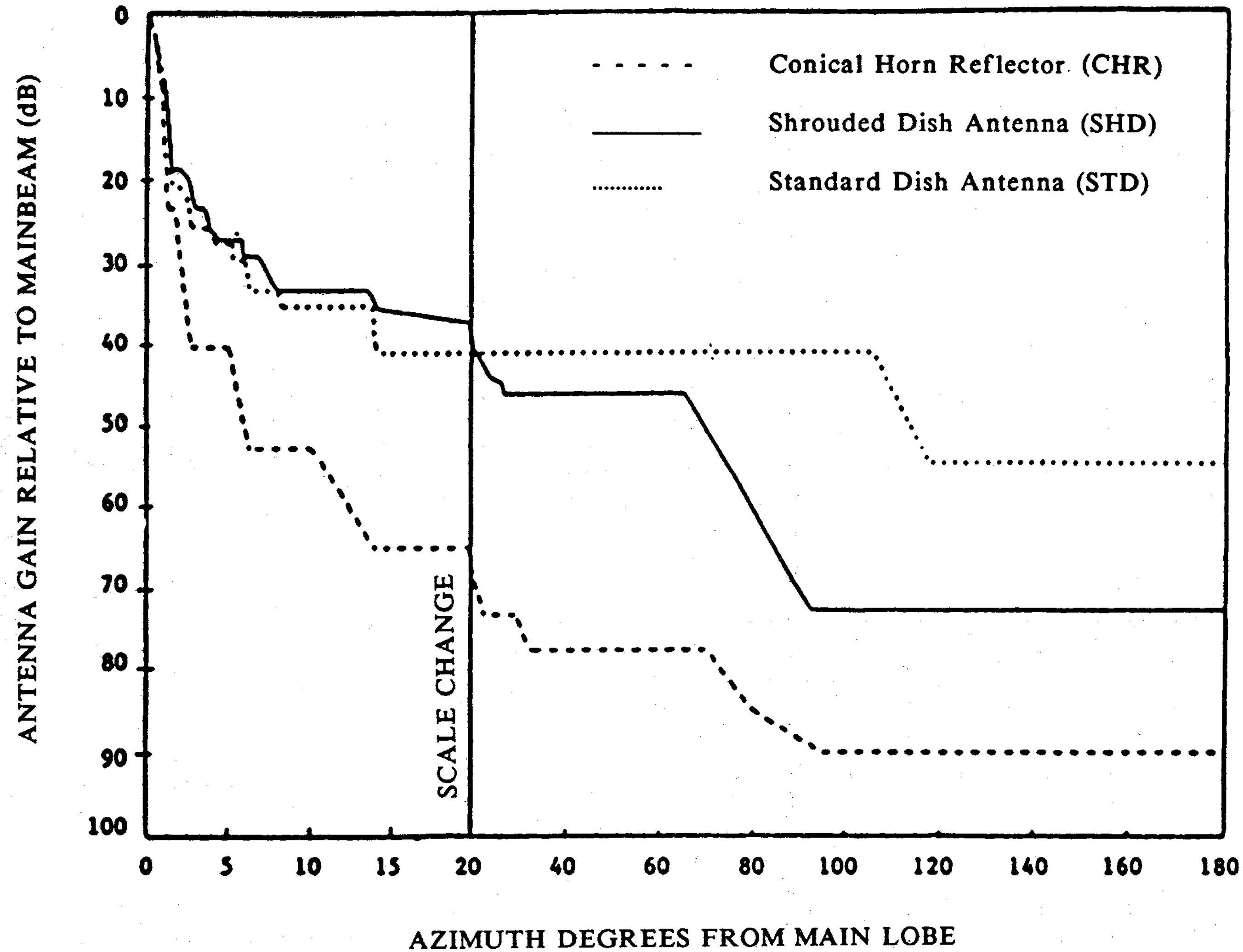


Figure 3-2. Radiation patterns for STD, CHR, SHD antennas.

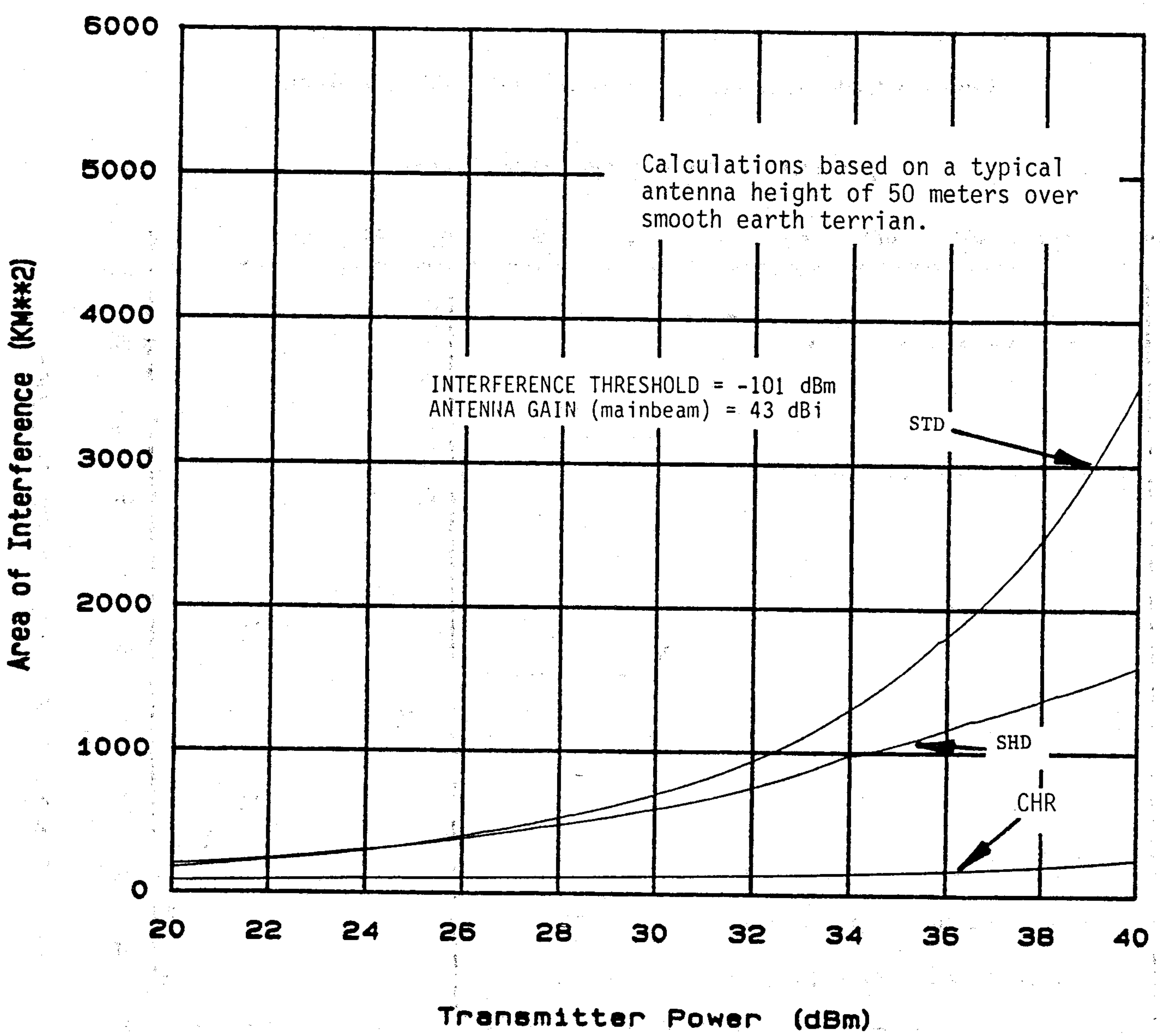


Figure 3-3. Denied area as a function of antenna type and transmitter output power for an interference threshold of -101 dBm.

antennas is small until the transmitter power is greater than 30 dBm. This is understandable because the contribution to the denial area caused by sidelobe/backlobe antenna characteristics is small until the transmitter power is increased beyond 30 dBm. At transmitter output powers greater than 30 dBm, the difference in denial area for the three types of antennas is significant. The denial area is also a function of the receiver interference threshold. Figure 3-4 shows the denial area for an interference threshold of -103 dBm. A comparison of Figures 3-3 and 3-4 shows a significant increase in denial area for only a 2 dB decrease in the interference threshold. Hence a general observation may be made that microwave systems that require higher transmitter power and/or lower interference thresholds generally need to use better antennas (i.e., antennas with lower sidelobe/backlobe characteristics).

Since the denied area for the three types of antennas is a function of the transmitter output power and the maximum permissible interference level, the spectrum conserving properties for the three antenna types must also be related to system modulation type. Thus the spectrum efficiency enhancement properties of the STD, SHD and CHR antennas will be discussed in the modulation section.

Antenna Cost

For the 7/8 GHz band, the cost of a standard parabolic dish antenna is approximately $2,700 for single polarization, and approximately $3,700 for dual polarization. The shrouded dish (SHD) antennas are substantially more bulkier, heavier and more expensive than the standard dish (STD) antenna. However, they are often used on the same antenna tower as the standard dish antenna. The cost of an SHD antenna is approximately three times a STD antenna, and cost approximately $8,000 for single polarization and $9,100 for dual polarization. A conical horn reflector (CHR) antenna is approximately $18,500, and requires a more substantial tower.

The cost of the antenna is approximately 5 to 10 percent of the total cost of a microwave system (building, radio equipment, tower and antenna). The relative percentage is a function of: 1) number of antennas per tower, 2) cost of radio communication equipment and 3) the number of transmitters and receivers using the same antenna. Therefore, the purchase of a more spectrum efficient antenna (SHD and CHR) generally will not have a major impact on the total system cost.

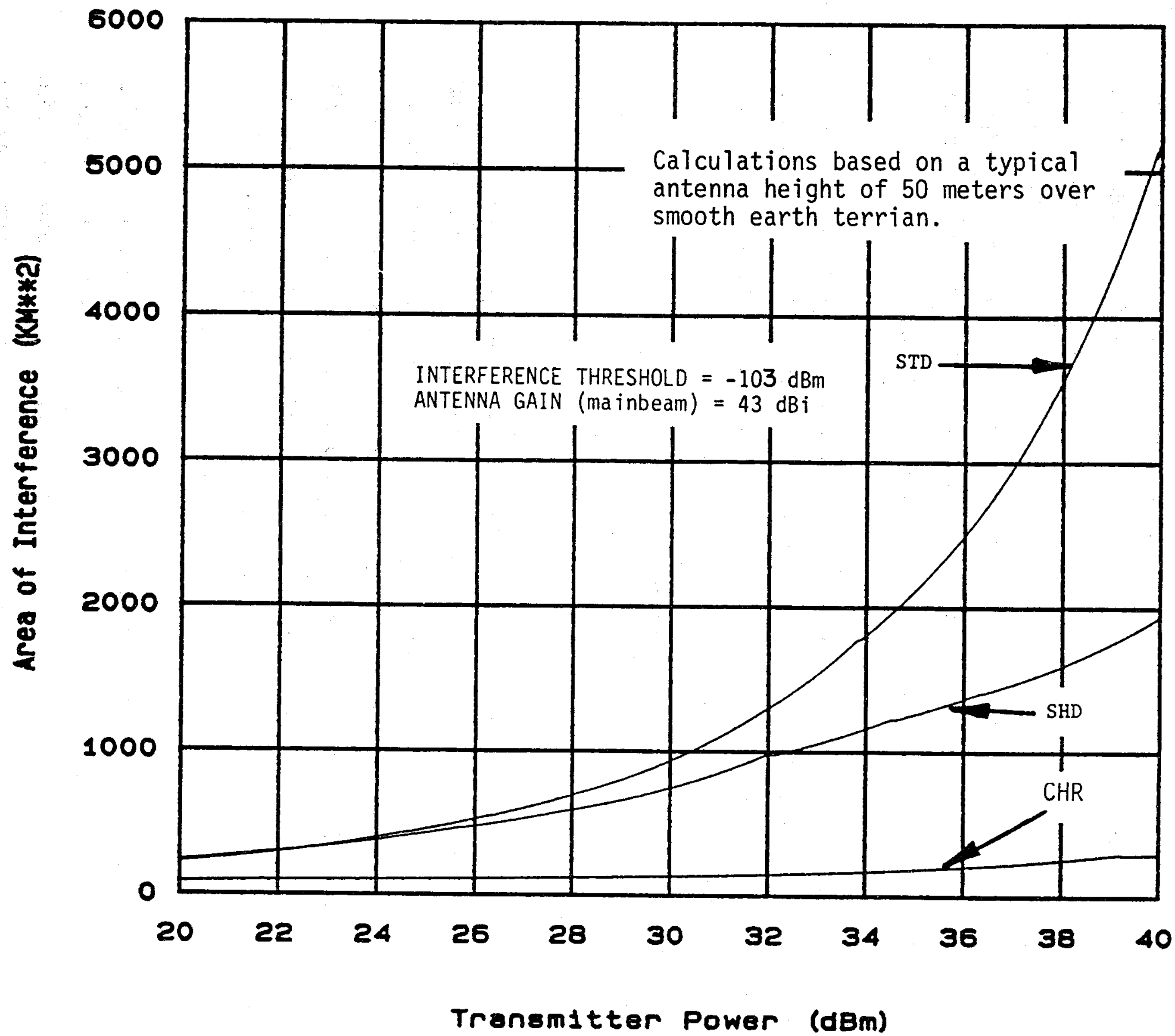


Figure 3-4. Denied area as a function of antenna type and transmitter output power for an interference threshold of -103 dBm.

MODULATION

The evaluation of spectrum conservation properties for different modulation schemes is very complex in that both spectrum and spacial denial are effected by the choice of modulation type used in a system. In general, system parameters such as occupied bandwidth, required receiver input carrier-to-noise ratio, $(C/N)_i$, and maximum permissible interference level are all functions of the modulation type and have a direct bearing on spectrum utilization. For most modulations, all these factors can be exchanged. For example, one can decrease the required occupied bandwidth, B, in a tradeoff for an increase in the required C/N ratio or vice versa. This tradeoff is given by the Shannon-Hartley Law.[6] The occupied bandwidth, B, is directly related to spectrum denial, and the required $(C/N)_i$ is indirectly related to spatial (area) denial since an increase in the required $(C/N)_i$ requires an increase in required transmitter output power.

In this analysis eight different modulation types often used in fixed service point-to-point microwave systems were considered. The analysis utilized theoretical parameters for the different modulation types instead of manufacturer specifications and measured performance information to ensure a just comparison. In order to evaluate the spectrum conservation properties for the different modulation types it was necessary to determine the occupied bandwidth, required transmitter output power level and maximum permissible interference level for each modulation type.

Digital Modulation

The following is a discussion of the determination of occupied bandwidth and required transmitter output power level for the digital modulations analyzed. In order to analyze the spectrum conservation properties of different digital modulation it is necessary to establish reference system characteristics to do the analysis. The reference system characteristics assumed here were:

---

6 B. P. Lathi, Communication Systems, John Wiley & Sons, Inc. (1965).

1. BITS PER SAMPLE (n) = 8
2. SAMPLE RATE = 8 kHz
3. NUMBER OF VOICE CHANNELS = 1344
4. TRANSMISSION RATE (R) = 90 Mb/s (TWO DS3 TIME-DIVISION MULTIPLEXERS)
5. BIT ERROR RATE (BER) = 10^{-6}
6. THEORETICAL TRANSMISSION EFFICIENCY AND C/N

   -IDEAL RECEIVER IF AND LP FILTERS

   -NO INTERSYMBOL INTERFERENCE

The digital modulations considered in this investigation are: phase shift keying (4-PSK and 8-PSK), quadrature amplitude modulation (16-QAM, 64-QAM and 256-QAM) and quadrature partial response signaling (9-QPRS).

Digital System Occupied Bandwidth

The occupied bandwidth, B, for the digital modulations was determined using the relationship

$$B = \frac{R}{\log_2 M} \tag{3-2}$$

where:

R = Transmission Rate (b/s), 90 Mb/s
M = Equivalent number of states
$\log_2 M$ = Transmission Efficiency

The transmission efficiency and occupied bandwidth for each of the digital modulations are given in TABLE 3-3.

Digital System Transmitter Output Power

In order to establish the required transmitter output power for each digital modulation type, it is necessary to determine the required receiver $(C/N)_i$, for a specified performance criteria. For the digital modulations, a bit error rate (BER) of 10^{-6} was used as the performance criteria and the required receiver $(C/N)_i$ was obtained from open literature.[7,8,9]

The receiver input noise level given in TABLE 3-3 was determined from the relationship:

$$N_i = -114 \text{ dBm} + 10\log B \text{ (MHz)} + NF \qquad (3\text{-}3)$$

where NF is the receiver noise figure (assumed to be 7 dB). The required minimum carrier level C(min) at the receiver input was then determined from:

$$C(min) = (C/N)_i + N_i \qquad (3\text{-}4)$$

The required transmitter output power, P_t, given in TABLE 3-3 is related to C(min) by the expression:

$$P_t = C(min) + G_S \qquad (3\text{-}5)$$

where G_S represents the system gain which was set equal to 103 dB.

TABLE 3-3 summarizes the required occupied bandwidth, B, required transmitter output power level, P_t, and gives the transmission efficiency (Bits/second/Hz) for all the digital modulations studied.

---

7 Kamilo Feher, Digital Communications, Microwave, Applications, Prentice-Hall Inc., Englewood Cliffs, N.J., (1981).

8 Kamilo Feher, Edward M. Karkar, and John D.Y. Huang, "On 6.67 b/s/Hz-256-QAM and 225-QPRS Modems for T1/SG Data-in-Voice Applications," IEEE (1985).

9 J. A. Crossett and P. R. Hartmann, "64-QAM Digital Radio Transmission System Integration and Performance," IEEE (1984).

Analog Modulation

The following is a discussion of the determination of occupied bandwidth and required transmitter output power level for the analog modulations analyzed. In order

TABLE 3-3

DIGITAL SYSTEM PARAMETERS
(90 Mb/s)

MODULATION TYPE	TRANSMISSION EFFICIENCY (b/s/Hz)	BANDWIDTH (MHz)	REQUIRED CARRIER-TO-NOISE (dB)	NOISE LEVEL (dBm)	MINIMUM CARRIER LEVEL (dBm)	TRANSMITTER POWER LEVEL (dBm)
4 PSK	2	45	13.6	-90.5	-76.9	26.1
8 PSK	3	30	19.0	-92.2	-73.2	29.8
9 QPRS	2	45	16.6	-90.5	-73.9	29.1
16 QAM	4	22.5	21.0	-93.5	-72.5	30.5
64 QAM	6	15	27.0	-95.2	-68.2	34.8
256 QAM	8	11.25	33.1	-96.5	-63.4	39.6

to analyze the spectrum conservation properties of different analog modulations, it is necessary to establish reference system characteristics to do the analysis. The reference system characteristics assumed for analysis of the spectrum conservation properties of analog modulation systems were:

1. NUMBER OF VOICE CHANNELS (N) = 600 (FDM/FM)
   1200 (FDM/FM)
   5400 (FDM/SSB)
2. CHANNEL BANDWIDTH (b) = 3.1 kHz
3. OUTPUT SIGNAL-TO-NOISE RATIO $(S/N)_o$ = 30 dB
4. MAXIMUM BASEBAND FREQUENCY (f_m) = 3024 kHz for 600 (FDM/FM)
   5772 kHz for 1200 (FDM/FM)
5. RMS TEST-TONE DEVIATION (f_r) = 200 kHz for 600 (FDM/FM)
   = 140 kHz for 1200 (FDM/FM)
6. NOISE LOADING FACTOR (NLF) = -15 + 10log N (FDM/FM)
   -19.6 + 10log N (FDM/SSB)

Analog System Occupied Bandwidth

The occupied bandwidth for the FDM/FM systems was determined using Carson's rule.

$$B = 2[3.76gf_r + f_m] \quad (3\text{-}6)$$

Where:

f_r = rms test-tone deviation
f_m = maximum baseband frequency
g = $10^{NLF/20}$
NLF = -15 + 10log N
N = number of voice channels

Using Equation 3-6 and the parameters given above for the FDM/FM systems, the occupied bandwidth for the 600 and 1200 channel FDM/FM are 13 MHZ and 18 MHz respectively.

The occupied bandwidth for the single sideband (SSB) system was based on the theoretical required baseband bandwidth which is 30 MHz.

TABLE 3-4 summarizes the required occupied bandwidth, B, for the analog systems and gives the system channel efficiency (voice channels per MHz).

Analog System Transmitter Output Power

In order to establish the required transmitter output power for each analog modulation type, it is necessary to determine the required receiver $(C/N)_i$ for a specified performance criteria. For the analog modulations, a 30 dB output signal-to-noise ratio $[(S/N)_o]$ was used as the performance criteria. This output ratio, $[(S/N)_o]$, is often referred to as the signal-to-noise output Test Tone ratio. The required input carrier-to-noise ratio for the FDM/FM systems was obtained from the following equation.

$$(C/N)_i = (S/N)_o - 10\log[(B/b)(f_r/f_m)^2] - W \quad (3\text{-}7)$$

Where:

b = Channel bandwidth = 3.1 kHz
W = Pre-emphasis weighing factor = 2.5 dB

TABLE 3-4

ANALOG SYSTEM PARAMETERS

Modulation Type	Channel Efficiency (vc/MHz)	Bandwidth (MHz)	Required Carrier-To-Noise (dB)	Noise Level (dBm)	Minimum Carrier Level (dBm)	Transmitter Power (dBm)
FDM/FM (1200)	70	18	17.8	-95	-77.2	25.8
FDM/FM (600)	40	13	10.5	-96	-85.5	17.5
SSB (5400)	180	30	8.2	-92.2	-84.0	19.0

Applying Equation 3-7 the required input carrier-to-noise ratio for the 600 and 1200 channel FDM/FM systems is 10.5 and 17.8 dB respectively.

The required input carrier-to-noise ratio for the 5400 channel FDM/SSB system was determined using a baseband signal test tone (T_T) level of -104 dBm which is required for an output signal-to-noise ratio of 30 dB given a channel noise level, N_c, specified in dBm by:

$$N_c = -174 \text{ dBm} + 10\log(3100) + NF \quad (3\text{-}8)$$

Where:

NF = receiver noise figure = 7 dB (typical)

For a FDM/SSB system, the required input carrier level in dBm is given by:

$$C_i = T_T + NLF = -84 \text{ dBm} \quad (3\text{-}9)$$

Where:

T_T = -104 dBm
$NLF = -19.6 + 10\log(5400) = 18$ dB

The receiver input equivalent noise level in dBm is given by:

$$N_i = -114 + 10\log B(MHz) + NF = -92.2 \text{ dBm} \quad (3\text{-}10)$$

Where:

B = receiver occupied bandwidth = 30 MHz
NF = receiver noise figure = 7 dB

The required receiver input carrier-to-noise ratio, $(C/N)_i$, can now be determined from Equations 3-9 and 3-10.

$$(C/N)_i = C_i - N_i = -84 \text{ dBm} - (-92.2 \text{ dBm}) = 8 \text{ dB} \quad (3\text{-}11)$$

TABLE 3-4 summarizes the required receiver $(C/N)_i$ for the analog systems. The receiver input noise levels, N_i, and minimum carrier levels, C(min), given in TABLE 3-4 were determined using Equation 3-3 and 3-4 respectively. The required transmitter output power level, P_t, was calculated using Equation 3-5. TABLE 3-4 also shows the number of voice channels (VC) and channel efficiency (VC/MHz) for each of the analog modulations.

Maximum Permissible Interference Level

The receiver maximum permissible interference level associated with each modulation was determined assuming that the victim receiver has the same modulation type as the transmitter. Therefore, the maximum permissible interference level will vary as a function of the modulation type. This assumption was based on the premise that if a standard modulation was adopted based on spectrum conservation properties, the environment will become homogeneous. That is the interfering transmitter and the victim receiver will have the same modulation type. In this analysis the maximum permissible interference level was determined using the criteria established in the Electronic Industries Association Standard (EIA Bulletin no. 10-D).[10]

---

10 Electronic Industries Association, Telecommunications Systems Bulletin No. 10D, "Interference Criteria for Microwave Systems in the Private Radio Service," August 1983.

Digital Systems. For the digital systems, the performance criteria used was a decrease in BER from 10^{-6} to 10^{-5} which corresponds to approximately a one dB increase in receiver noise level at the receiver input ([I + N]/N = 1 dB) and is equivalent to an interference-to-noise (I/N) ratio at the receiver input of -6 dB. Based on the receiver input noise levels given in TABLE 3-3, the maximum permissible interference level I_{MAX}, for each digital modulation type was calculated using:

$$I_{MAX} = N_i - 6 \qquad (3\text{-}12)$$

TABLE 3-5 summarizes the maximum permissible interference levels for all the digital modulations types, and gives the corresponding faded and unfaded receiver input carrier levels (C_i) and carrier-to-interference ratios [$(C/I)_i$], assuming a 40 dB fade margin.

Analog Systems. For the analog systems, the performance criteria used was a 5 pWp0 interference level in a channel for a single hop which is accepted by the Electronic Industries Association (EIA Bulletin no. 10-D). For 600 and 1200 channel FDM/FM systems, the Electronic Industries Association Standard (EIA Bulletin no. 10-D) specifies an unfaded receiver $(C/I)_i$ at the receiver input of 69 and 73 dB respectively. EIA does not specify a receiver input carrier-to-interference ratio for a FDM/SSB 5400 channel system; however, for a performance criteria of 5 pWp0, the required unfaded carrier-to-interference ratio at the receiver was determined to be 66 dB. Using the carrier levels given in TABLE 3-4 and taking into account a 40 dB fade margin, the maximum permissible interference level for the analog systems was determined by:

$$I_{MAX} = C_i - (C/I)_i + 40 \qquad (3\text{-}13)$$

The maximum permissible interference level for each of the analog modulation types is given in TABLE 3-5.

TABLE 3-5

MAXIMUM PERMISSIBLE INTERFERENCE FOR DIFFERENT MODULATION TYPES

MODULATION TYPE	NOISE LEVEL (dBm)	FADED CARRIER (dBm)	UNFADED CARRIER LEVEL (dBm)	FADED C/I RATIO (dB)	UNFADED C/I RATIO (dB)	I/N RATIO (dB)	INTERFERENCE LEVEL[1] (dBm)
4 PSK	-90.5	-76.9	-36.9	20.4	60.4	-6[2]	-97
8 PSK	-92.2	-73.2	-33.2	25.0	65.0	-6[2]	-98
9 QPRS	-90.5	-73.9	-33.9	22.6	62.6	-6[2]	-97
16 QAM	-93.5	-72.5	-32.5	27.0	67.0	-6[2]	-100
64 QAM	-95.2	-68.2	-28.2	33.0	73.0	-6[2]	-101
256 QAM	-96.5	-63.4	-23.4	39.1	79.1	-6[2]	-103
FM (1200 ch)	-95.0	-77.2	-37.2	33.0	73.0[3]	-15.2	-110
FM (600 ch)	-96.0	-85.5	-45.5	29.0	69.0[3]	-18.5	-115
SSB	-92.2	-84.0	-44.0	26.0	66.0	-17.8	-110

1. Entries are rounded to the nearest integer.

2. The Electronic Industries Association performance degradation criterion for digital systems is a decrease in BER from 10^{-6} to 10^{-5} which corresponds appproximately to 1 dB increase in noise level. An interference-to-noise ratio of -6 dB is nearly equivalent to an interference plus noise-to-noise ratio of 1 dB.

3. Electronic Industries Association Performance criteria (EIA Bulletin No. 10-D).

Spectrum Conservation Factor

TABLE 3-6 contains the calculated spectrum conservation factor (SCF) value for each of the different modulation types using the system bandwidth and transmitter output power level given in TABLES 3-3 and 3-4 and the maximum permissible interference level given in TABLE 3-5. The entries for SCF in TABLE 3-6 are for nine different modulation types and three types of antennas (STD, SHD and CHR). Systems with higher SCF values are more efficient from the spectrum conservation point-of-view. It should be emphasized that the calculated results clearly point out that for the majority of the modulations the SCF varies considerably from one antenna type to another. For example, the SCF for 64-QAM is 0.060 for the STD antenna as compared to 0.086 and 0.056 for the SHD and CHR antennas, respectively. Therefore TABLE 3-6 indicates that the SCF can be optimized only when the effects of both antenna and modulation are considered together. Improvement or even change in any one of the factors alone in a system does not always result in the optimum SCF for that system. SCF may be used to select a combination of system design factors that result in an optimum use of the spectrum.

TABLE 3-6 indicates that, regardless of the antenna type used, FDM/SSB modulation has higher SCF values than the systems using other modulation types. This is due to new developments capabilities in the suppression of intermodulation noise and the ability of the FDM/SSB system to accommodate a large number of channels in a relatively small bandwidth.

In addition, by comparison, the SCF for 64-QAM was found to be higher than that for the 256-QAM for all three antenna types. Hence the analysis results indicate that 64-QAM is a more spectrum conserving modulation based on the SCF concept. TABLE 3-7 provides as explanation of why 64-QAM is more spectrum efficient than 256-QAM for a shrouded dish (SHD) antenna. The input parameters to the model are provided in the table. The number of voice channels (VC) is the same, 1344, for both modulations since two DS3s are assumed. The required system bandwidth, B, for 256-QAM is smaller than for 64-QAM (11.25 MHz as compared to 15 MHz). However, the required transmitter power level, P_t, for 256-QAM is significantly higher than 64-QAM (39.6 dBm as compared to 34.8 dBm), and the transmitter power has a major effect on

TABLE 3-6

SPECTRUM CONSERVATION FACTOR FOR ANALOG AND DIGITAL MODULATIONS (EIA INTERFERENCE THRESHOLD USED)*

	Spectrum Conservation Factor For Different Antenna Types		
Ranking Order	STD (SCF)	SHD (SCF)	CHR (SCF)
1	FDM/SSB (0.337)	FDM/SSB (0.372)	FDM/SSB (1.553)
2	4-PSK (0.128)	4-PSK (0.121)	64-QAM (0.560)
3	8-PSK (0.099)	8-PSK (0.105)	16-QAM (0.489)
4	16-QAM (0.092)	16-QAM (0.106)	FM (1200) (0.416)
5	9-QPRS (0.085)	64-QAM (0.086)	256-QAM (0.403)
6	64-QAM (0.060)	9-QPRS (0.086)	8-PSK (0.402)
7	FM (600) (0.053)	FM (600) (0.065)	FM (600) (0.347)
8	FM (1200) (0.045)	FM (1200) (0.064)	4-PSK (0.324)
9	256-QAM (0.025)	256-QAM (0.064)	9-QPRS (0.281)

* see TABLE 3-5

denied area to another user (see Figures 3-3 and 3-4). Also the 256-QAM is more susceptible to interference than 64-QAM, thus requiring a lower maximum permissible interference level (-103 dBm as compared to -101 dBm). The lower maximum permissible interference level also increases the denied area to another user. In summary, 64-QAM is more spectrum conserving (i.e., higher SCF value) than 256-QAM for all antenna types considered. It should be noted that the transmission efficiency (bits/s/Hz) of 64-QAM is 6 bits/s/Hz as compared to 8 bits/s/Hz for 256-QAM. Therefore, the transmission efficiency may not suffice as an indicator of spectrum conservation.

TABLE 3-7
SPECTRUM CONSERVATION FACTOR COMPARISON OF
64- AND 256- QAM FOR SHD ANTENNA

PARAMETER	64-QAM	256-QAM	
VC	1344	1344	
B	15 MHz	11.25 MHz	(See TABLE 3-3)
P_t	34.8 dBm	39.6 dBm	(See TABLE 3-3)
I_{MAX}	-101 dBm	-103 dBm	(See TABLE 3-5)
A	1040 km^2	1859 km^2	(See Figures 3-3 & 3-4)
SCF	0.086	0.064	(See TABLE 3-6)

TABLE 3-6 can also be used to determine the relative improvement in spectrum conservation of using a shrouded dish (SHD) antenna or conical horn reflector (CHR) antenna over a standard dish (STD) antenna. As stated earlier, the improvement in spectrum conservation for the SHD and CHR antenna is dependent on the modulation type. This is due to the fact that the denial area produced by a particular antenna type is a function of the required transmitter output power (P_t) and maximum permissible interference level (I_{MAX}) which are modulation dependent (See Figures 3-3 and 3-4). TABLE 3-8 shows the percentage improvement in Spectrum Conservation Factor (SCF) for the various modulations addressed using the SCF data in TABLE 3-6.

TABLE 3-8

SPECTRUM CONSERVATION FACTOR IMPROVEMENT FOR SHROUDED DISH AND CONICAL HORN REFLECTOR ANTENNAS AS A FUNCTION OF MODULATION TYPE

Modulation Type	Improvement In Spectrum Conservation Factor (SCF)	
	Shrouded Dish (SHD)	Conical Horn Reflector (CHR)
FDM/SSB	10%	360%
FDM/FM 600 Channel	23%	550%
FDM/FM 1200 Channel	42%	820%
4 PSK	-5%	150%
8 PSK	15%	310%
9 QPRS	1%	230%
16-QAM	14%	430%
64-QAM	43%	830%
256-QAM	156%	1500%

TABLE 3-9

SPECTRUM CONSERVATION FACTOR
FOR
ANALOG AND DIGITAL MODULATIONS
(EIA INTERFERENCE THRESHOLD USED)*

Ranking Order	Spectrum Conservation Factor For Different Antenna Types**		
	STD (SCF)	SHD (SCF)	CHR (SCF)
1	FDM/SSB (0.215)	FDM/SSB (0.205)	FDM/SSB (0.588)
2	4 PSK (0.077)	4 PSK (0.070)	64-QAM (0.237)
3	8 PSK (0.063)	8 PSK (0.058)	16-QAM (0.179)
4	16-QAM (0.058)	16-QAM (0.057)	FM (1200) (0.176)
5	9-QPRS (0.053)	64-QAM (0.047)	8 PSK (0.158)
6	64-QAM (0.041)	9 QPRS (0.046)	FM (600) (0.133)
7	FM (600) (0.033)	FM (600) (0.035)	4 PSK (0.133)
8	FM (1200) (0.030)	FM (1200) (0.035)	9 QPRS (0.115)
9	256-QAM (0.019)	256-QAM (0.030)	256-QAM (0.220)

* see TABLE 3-5
**Antenna Heights = 150 meters

TABLE 3-7 shows that for 4-PSK modulation the shrouded dish type antenna (SHD) does not offer an improvement in spectrum conservation. This is due to the fact that the shrouded dish antenna has higher sidelobe levels than the standard dish antenna for off axis angles less than 20 degrees (See Figure 3-2), and the required transmitter power and maximum permissible interference level associated with 4-PSK modulation. For the digital modulations, TABLE 3-8 clearly shows that as the digital modulation order increases the spectrum conservation improvement increases for a particular antenna type. The greatest improvement occurs for 256-QAM modulation with a 156 and 1512 percent increase for the shrouded dish (SHD) and conical horn reflector (CHR) antennas respectively.

To determine the sensitivity of the spectrum conservation factor (SCF) to scenario dependence, the computer model was also run for an antenna height of 150 meters. TABLE 3-9 shows the results for comparison with TABLE 3-6. In summary, the ranking order of the different modulation has changed. However, the FDM/SSB modulation remained the most spectrum efficient for all three antenna types, and 64-QAM is more spectrum efficient than 256-QAM for all three antenna types.

SIGNAL PROCESSING

In a fixed microwave communication system, signal processing is done at the transmitter and receiver terminal. Signal processing consists of electrical operations on a signal in order to produce certain desired characteristics. Signal processing can affect such parameters as amplitude, frequency, phase, signal level, reliability, etc.

The use of signal processing techniques can improve the processing gain of a system, permitting lower transmitter output power levels for specified receiver output performance criteria. Thus, through the use of signal processing techniques, the transmitter output power can be lowered reducing the spatial (area) denial of a system. However, it should be noted that signal processing techniques are used by the microwave link designers to improve link reliability and are not generally considered for the purpose of spectrum conservation.

Some signal processing techniques used in microwave systems are listed below.[11]

Companding -	the compression (at transmitter) and expansion (at receiver) of a signal to provide more gain to weak signals than to strong ones. Improves S/N on noisy speech circuits.
Pre-emphasis/De-emphasis -	(at the transmitter and receiver, respectively) used to ensure relatively constant S/N across the baseband of a system; this reduces transmitted carrier power, leading to a reduction in spatial denial.
Diversity -	radio signals propagating along separate paths to a common point may have noncorrelated signal levels upon arrival. Diversity transmission separates a transmitted signal on the basis of frequency, space, time, or polarization.
Adaptive Equalization -	employed to make digital radio receivers less susceptible to fading; can be implemented in either frequency or time domain.
Coding -	digital (block and convolution.)

Processing gains for each of the above signal processing techniques are given in TABLE 3-10.

Since the trend of fixed microwave equipment is toward digital systems, this study will only address error correction/coding and adaptive equalizer as a spectrum conservation technique.

Error Correction/Coding

Forward error correction (FEC) coding is a method of improving the BER performance of digital microwave systems, particularly when the system is power limited. The utilization of FEC coding techniques permits a limited number of errors to be corrected at the receiving end by means of special coding and software (or hardware) implemented at both ends of a circuit. This improvement in BER can be

---

11 Freeman, R. L., Telecommunication Transmission Handbook, 2nd Edition, John Wiley & Sons, (1981).

TABLE 3-10

PROCESSING GAIN SUMMARY

Signal Processing Techniques	Bandwidth Expansion Factor	Improvement (dB)
Preemphasis/Deemphasis	0	4
Frequency Diversity	2.0	1.5 to 6[a]
Space Diversity	0	1.5 to 6[a]
Polarization Diversity	0	1.5 to 6[a]
Adaptive Equalization	0	4 to b[b]
Coding	1.14 -2.0	0.6 to 6.2[c]

a. The 6 dB gain corresponds to using 4th order diversity (i.e., using space and frequency diversity) and a maximal ratio combiner. The 1.5 dB gain corresponds to using 2nd order diversity (i.e., using either space or frequency diversity) and a selector combiner.

b. This 4 to 6 dB range is the improvement that can be achieved in the composite fade margin using adaptive equalization in 64-QAM receivers.

c. 6.2 dB gain is based on using a convolutional code, with K = 24, R = 1/2. 0.6 dB gain is based on using a block hamming (7, 4) code type.

traded off for a reduction in required receiver input carrier-to-noise ratio [$(C/N)_i$] to meet a specified BER performance. The reduction in $(C/N)_i$ is referred to the coding gain.

There are two broad classes of codes: block codes and convolutional codes. With block-coding techniques, each group of K consecutive information bits is encoded into a group of N symbols for transmission over the channel. Normally, the K information bits are located at the beginning of the N-symbol block code, and the last N-K symbols correspond to the parity check bits formed by taking the modulo-2 sum of certain sets of K information bits. Because N symbols are use to represent K bits, the code rating, R, of such a block code is K/N bits per symbol. One inherent property of coding is the required occupied bandwidth, B, of a system is increased. This increase in required occupied bandwidth is called the bandwidth expansion factor of the code, and is equal to 1/R.

In summary, the performance of a coding technique is described by the coding gain and coding rate. The coding gain can be used to reduce the required receiver input $(C/N)_i$, thus reducing the denial area to other systems. However, the coding rate has an impact on the system occupied bandwidth, thus increasing the denied spectrum to other users of the spectrum.

To show the effect of coding on spectrum conservation, 64-QAM was selected as the modulation for study. Four types of FECs[12] [13] [14] were selected. TABLE 3-11 shows the coding rate, R, the bandwidth expansion factor, 1/R, the occupied bandwidth after coding, the reduction in $(C/N)_i$ for a BER of 10^{-6} and the required transmitter output power, P_t, after taking into consideration the obtainable reduction in C/N. The values for system bandwidth, B, and transmitter output power, P_t, shown in TABLE 3-11 were input to the spectrum conservation factor (SCF) model to evaluate coding as a spectrum conservation technique. TABLE 3-12 shows the SCF for the three types of antennas: STD, SHD and CHR. The SCF for 64-QAM without coding is also shown in the TABLE 3-12 for a baseline comparison of with and without coding.

In summary, the SCF values given in TABLE 3-12 indicate that signal processing techniques such as error correction/coding which utilize RF bandwidth versus carrier-to-noise trade-offs only provide improvement in spectrum conservation, higher SCF values, when high-efficiency coding techniques (i.e., coding techniques with high coding rates and coding gain) are used. Also, the relative improvement in spectrum conservation is greater when the system has an STD type antenna than an SHD or CHR type antenna. This is due to the fact that the reduction in denied area is greater for standard dish antennas because of the higher sidelobe/backlobe characteristics.

---

12 Bell Telephone Laboratories, Transmission Systems for Communications, Fifth Edition, Bell Laboratories, Inc. (1982).

13 G.D. Martin, "Optimal Convolutional Self-Orthoginal Codes With AN Application of Digital Radio," ICC '85, pp. 39.4.1-39.4.5, June 1985.

14 M. Kavehrad, "Convolutional Coding for High-Speed Microwave Radio Communications," AT&T Tech. Jour. vol. 64, no. 7, pp. 1625-1637, September 1985.

TABLE 3-11

ERROR CORRECTION/CODING (64-QAM MODULATION)

Signal Processing	Coding Rate	Bandwidth Expansion Factor	Bandwidth (MHz)	Reduction In C/N ($BER=10^{-6}$) (dB)	Transmitter Power (dBm)
Error correction coding	1/2	2	30.00	6	28.8
	3/4	1.333	20.00	3.5	31.3
	7/8	1.142	17.14	2.0	32.8
	18/19	1.055	15.83	3.0	31.8

TABLE 3-12

SPECTRUM CONSERVATION FACTOR FOR ERROR CORRECTION/CODING (64-QAM MODULATION)

Signal Processing Type		Spectrum Conservation Factor For Different Antenna Types		
		STD (SCF)	SHD (SCF)	CHR (SCF)
Without signal processing		0.060	0.086	0.560
	Coding Rate			
Error correction coding	1/2	0.076	0.085	0.376
	3/4	0.080	0.097	0.510
	7/8	0.073	0.094	0.553
	18/19	0.093	0.116	0.630

Adaptive/Transversal Equalizers

Adaptive/transversal equalizers improve the digital system performance in the presence of multipath fading, linear distortion, or both. The equalizers can only mitigate the dispersive aspects of multipath fading. There are two types of adaptive equalizers which are used in microwave receiver systems, transversal and decision feedback. These adaptive equalizers reshape the pulse so as to minimize the intersymbol interference. An approximate 4 to 6 dB improvement in the composite fade margin can be achieved with these equalizers in 64-QAM receivers. The major drawback of adaptive equalizers is their expense. The spectrum conservation factor (SCF) model was run for a system bandwidth, B, of 15 MHz and a transmitter output power, P_t, of 30.8 dBm (A 4.0 dB reduction in P_t for 64-QAM). TABLE 3-13 shows the SCF for the three types of antennas: STD, SHD and CHR. The SCF values without adaptive equalizers is also shown in the table for baseline comparison with adaptive equalizers.

For 64 QAM, The use of adaptive equalizers can improve the spectrum conservation properties of a system from 25 to 90 percent with the greatest improvement in systems that use standard dish (STD) type antennas.

Error Correction/Coding And Adaptive Equalizers

Some digital systems utilize both error correction/coding and adaptive equalizers to improve system performance. For 64-QAM, the utilization of error correction/coding (18/19 code rate) and adaptive equalizers can reduce the required input carrier-to-noise, $(C/N)_i$, ratio by 7 dB for BER = 10^{-6}. The application of the Spectrum Conservation Factor (SCF) model for a system bandwith, B, of 15.83 MHz and a transmitter output power, P_t, of 27.8 dBm (A 7.0 dB reduction in P_t for 64-QAM) is shown in TABLE 3-14. TABLE 3-14 shows that the use of error correction/coding and adaptive equalizers can improve the spectrum conservation properties of a system from 30 to 170 percent with the greatest improvement in systems that use dish type antennas.

TABLE 3-13

SPECTRUM CONSERVATION FACTOR FOR ADAPTIVE EQUALIZER (64-QAM MODULATION)

Signal Processing Type	Spectrum Conservation Factor For Different Antenna Types		
	STD (SCF)	SHD (SCF)	CHR (SCF)
Without signal processing	0.060	0.086	0.560
With adaptive equalizers	0.114	0.137	0.695

TABLE 3-14

SPECTRUM CONSERVATION FACTOR FOR ERROR CORRECTION/CODING AND ADAPTIVE EQUALIZERS (64-QAM MODULATION)

Signal Processing Type	Spectrum Conservation Factor For Different Antenna Types		
	STD (SCF)	SHD (SCF)	CHR (SCF)
Without signal processing	0.060	0.086	0.560
Error correction/coding and equalizers	0.164	0.179	0.737

APPENDIX A
COMPUTER MODEL DESCRIPTION

INTRODUCTION

This appendix contains a description of the computer model used to calculate the spectrum conservation factor (SCF), Equation 3-1, in evaluating spectrum conservation techniques for fixed point-to-point microwave systems. Also provided in this appendix are a model flow diagram and model output example.

MODEL DESCRIPTION

The computer model developed during this investigation is a Fortran code which calculates the spectrum conservation factor (SCF) defined as

$$SCF = \frac{VC}{T*B*A} \qquad \text{(A-1)}$$

where:

VC = Number of voice channels.
T = Fraction of time a system is used. Defined to be equal to 1 for this analysis.
B = Receiver System Bandwidth (MHz)
A = Denial area (km^2)

The number of voice channels, fraction of time and receiver system bandwidth are model input parameters. The denial area is a function of the transmitter output power level, P_t, maximum permissible interference level (interference threshold), I_{MAX}, and transmitter antenna pattern characteristics which are also input parameters to the model.

Denial Area

The algorithm used to calculate the denial area involves the segmentation (quantization) of the transmitter antenna gain pattern into a number of segments, n, as

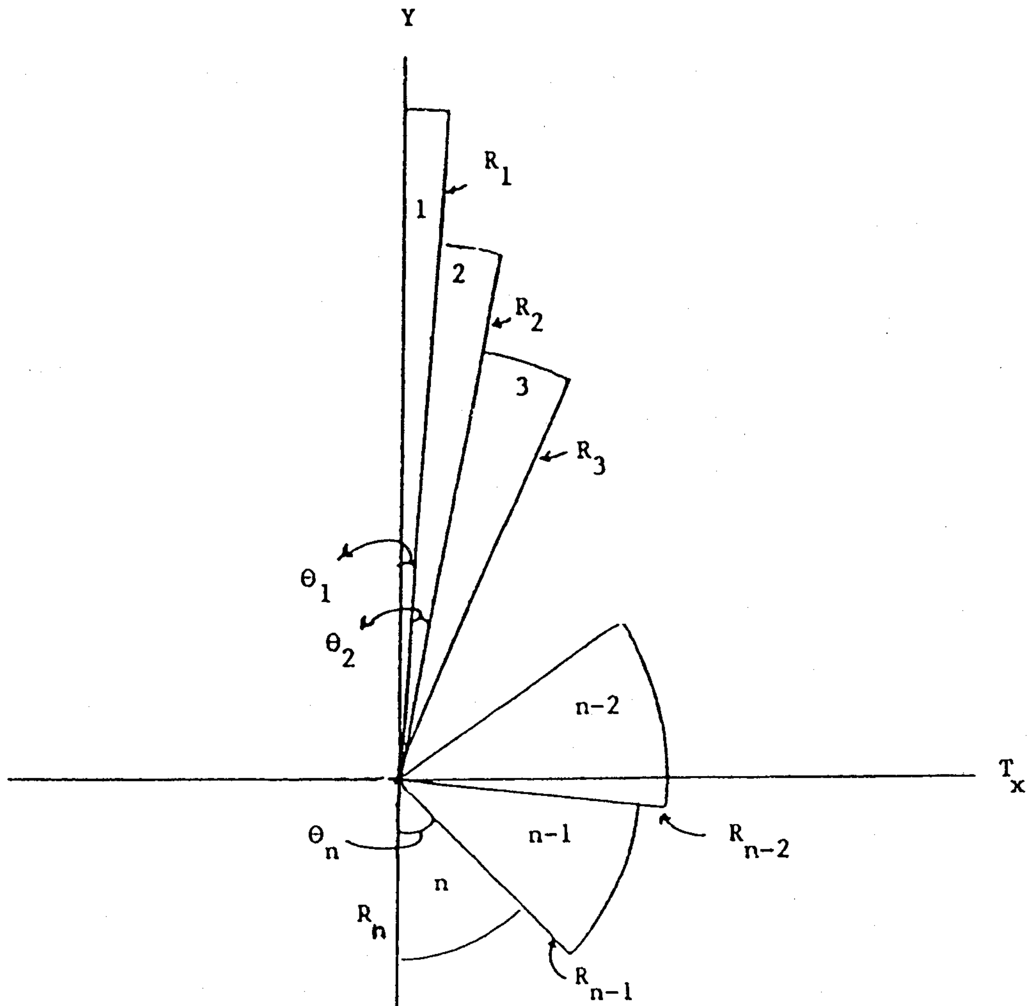


Figure A-1. Representation of antenna pattern by n circular sectors each representing a lobe.

shown in Figure A-1. The transmitter antenna gain pattern is an input to the model. The program calculates the denial area by summing the area in each segment from 0 to 180 degrees and multiplies the area by two to obtain the total denied area 360 degrees around the microwave transmitter. The antenna gain for each segment was obtained from measured antenna pattern data (see Figure 3-2). TABLE A-1 shows the segmented antenna pattern gain data used in the model for each of the antenna types discussed in SECTION 3. Geometrically, each segment is a circular sector, the area of which may be calculated using the formula

$$\text{Area of circular sector} = \pi R^2 \theta / 360 \qquad \text{(A-2)}$$

where:

R = radius of sector (R_1 , R_2, ..., R_n)
θ = vertex angle of sector (0_1, 0_2, ..., 0_n)

The radii R_n for each segment were calculated by the computer model using the relationship

$$L(R) = P_t + G_t(n) + G_r - I_{MAX} \qquad \text{(A-3)}$$

where:

$L(R)$	=	Required propagation loss, in dB
P_t	=	Transmitter output power, in dBm
$G_t(n)$	=	Transmitter antenna gain at sector n, in dBi
G_r	=	Receiver antenna gain, 0 dBi
I_{MAX}	=	Maximum permissible interference level (interference Threshold), in dBm

Then using as algorithm similar to inverse propagation model the distance R corresponding to the required loss is evaluated by the model. This facilitates the evaluation of the denial area for each circular sector, (see Equation A-2).

TABLE A-1

ANTENNA PATTERN DATA USED IN THE ANALYSIS

	STD Antenna		SHD Antenna		CHR Antenna	
No.	Antenna Sector Gain (dBi)	Angle (deg.)	Antenna Sector Gain (dBi)	Angle (deg.)	Antenna Sector Gain (dBi)	Angle (deg.)
1	43.0	0.005	43.0	0.005	43.0	0.010
2	42.1	0.395	42.3	0.495	42.9	0.100
3	39.1	0.400	39.8	0.300	42.6	0.100
4	30.9	0.500	35.1	0.300	42.2	0.100
5	22.7	0.200	24.2	1.100	41.4	0.100
6	21.8	0.800	23.5	0.400	40.0	0.200
7	17.9	0.500	19.9	1.000	36.6	0.200
8	17.2	1.100	17.1	0.400	33.4	0.100
9	15.5	1.300	17.0	0.300	26.2	0.300
10	13.5	0.200	16.1	0.100	20.0	0.600
11	13.4	0.700	16.0	1.500	2.5	3.20
12	9.8	0.200	13.9	1.000	-10.0	5.000
13	9.7	1.700	9.8	1.000	-22.0	10.000
14	7.9	5.900	9.7	5.800	-30.2	10.000
15	3.0	0.200	7.2	4.400	-35.0	40.000
16	2.0	0.200	5.5	0.200	-42.1	10.000
17	1.8	91.500	5.4	2.500	-47.0	100.000
18	-12.0	74.200	3.0	0.300		
19			0.5	1.300		
20			-1.1	1.700		
21			-1.7	2.700		
22			-3.0	39.100		
23			-12.0	12.000		
24			-21.0	12.000		
25			-30.0	90.000		

COMPUTER MODEL FEATURES

The computer model has several special features. The parameter IMODE is used to evaluate the denial area for a single transmitter power level (IMODE=1) or a number of transmitter power levels (IMODE=2). The program output is stored in two separate files with the file menus selected by the user. One file contains the detail of the calculation as well as the input data which help the user to check again the original data. The other file is for plotting the calculated results. The data is this file are arranged in two columns. One column contains the data on the transmitter power and the other column the corresponding data on the denial area. The data in this file has a format compatible with TCPLT, an interactive plot routine which may be accessed through VAX or PCs. A model flow diagram is shown in Figure A-2.

PROGRAM INPUT PARAMETERS

TABLE A-2 given below contains a description of the input parameters for the SCF model.

TABLE A-2

DESCRIPTION OF MODEL PARAMETERS

IMODE	=	Mode of operation
BANDW	=	Receiver system bandwidth (MHz)
THRES	=	Interference threshold (dBm)
NCHANEL	=	Number of voice channels
TFREQ	=	Transmitter frequency (MHz)
PTI	=	Initial Transmitter power (dBm)
HTXM	=	Transmitter antenna height (km)
HRXM	=	Receiver antenna height (km)
NUMANT	=	Number of antenna
NLOBES	=	Number of antenna segments

SCF MODEL OUTPUT EXAMPLE

TABLE A-3 shows an example output for 64 QAM modulation with a shrouded dish (SHD) antenna.

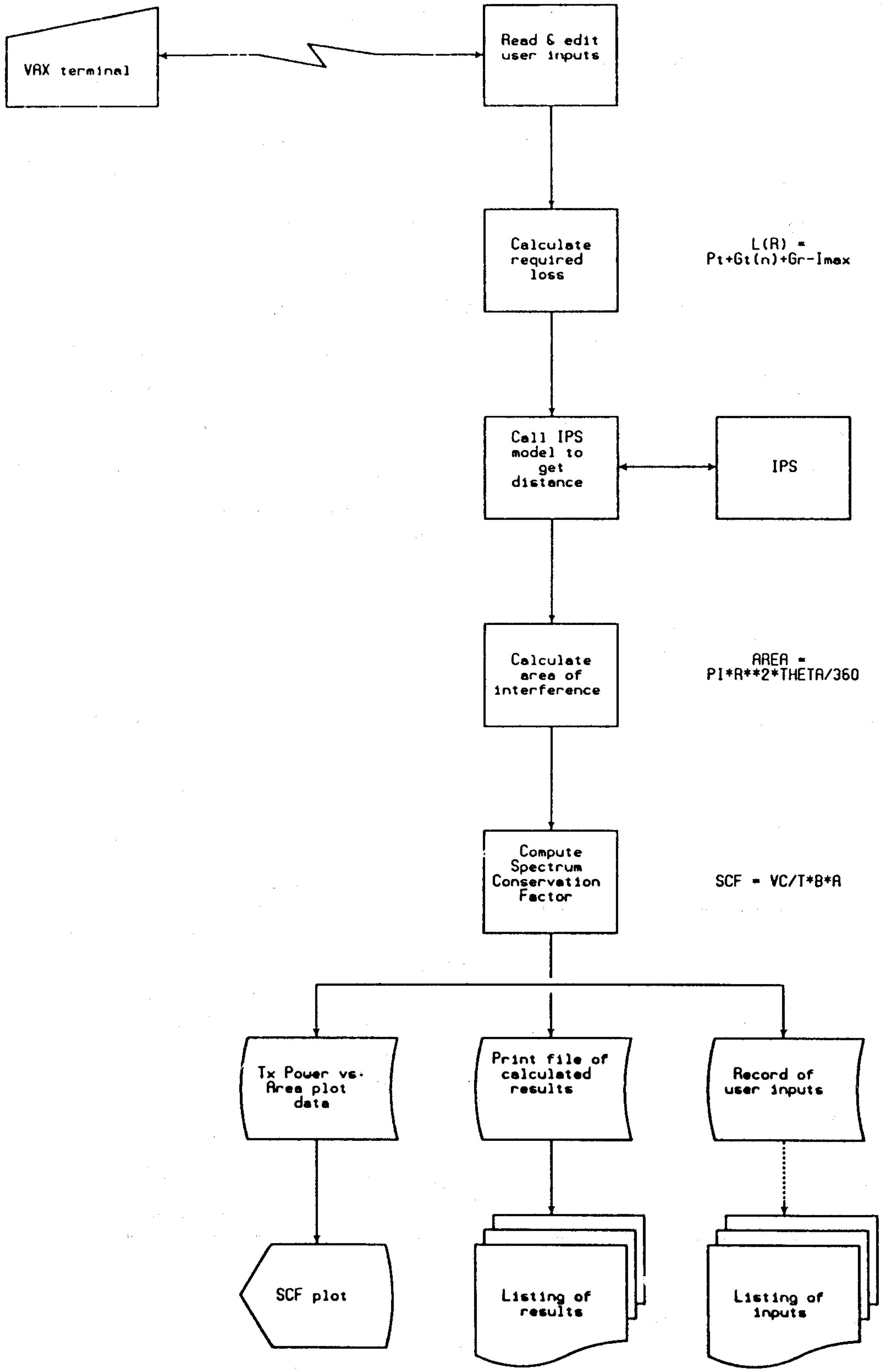


Figure A-2. Spectrum Conservation Factor (SCF) Model Flow Diagram.

TABLE A-3

MODEL EXAMPLE OUTPUT

```
*************************************************************
*  S P E C T R U M   C O N S E R V A T I O N   F A C T O R  *
*                       PROGRAM SCF                         *
*                      NTIA VAX/VMS                         *
*************************************************************
```

ANTENNA NO. 2
TRANSMITTER FREQUENCY (MHZ) = 8000.0
TRANSMITTER ANTENNA HEIGHT (M) = 50.00
RECEIVER ANTENNA HEIGHT (M) = 50.00
TIME (%) = 1.0
BANDWIDTH (MHZ) = 15.0
DENIED RECEIVER THRESHOLD (DBM) = -101.0
NUMBER OF CHANNELS = 1344

POWER (DBM)	SECTOR NUMBER	ANTENNA SECTOR GAIN (DBI)	ANTENNA SECTOR ANGLE (DEGREES)	REQUIRED LOSS (DB)	SECTOR RADIUS (KM)	SECTOR AREA*2 (KM**2)
34.800	1	43.000	0.005	178.800	69.281	0.42
34.800	2	42.300	0.495	179.100	68.854	40.96
34.800	3	39.800	0.300	175.600	67.339	23.74
34.800	4	35.100	0.300	170.900	64.534	21.81
34.800	5	24.200	1.100	160.000	58.247	65.14
34.800	6	23.500	0.400	159.300	57.854	23.37
34.800	7	19.900	1.000	155.700	55.853	54.45
34.800	8	17.100	0.400	152.900	54.319	20.60
34.800	9	17.000	0.300	152.800	54.266	15.42
34.800	10	16.100	0.100	151.900	53.777	5.05
34.800	11	16.000	1.500	151.800	53.723	75.56
34.800	12	13.900	1.000	149.700	52.592	48.27
34.800	13	9.800	1.000	145.600	50.420	44.37
34.800	14	9.700	5.800	145.500	50.367	256.81
34.800	15	7.200	4.400	143.000	42.152	136.45
34.800	16	5.500	0.200	141.300	34.659	4.19
34.800	17	5.400	2.500	141.200	34.263	51.22
34.800	18	3.000	0.300	139.800	25.991	3.54
34.800	19	0.500	1.300	136.300	19.490	8.62
34.800	20	-1.100	1.700	134.700	16.211	7.80
34.800	21	-1.700	2.700	134.100	15.129	10.79
34.800	22	-3.000	39.100	132.800	13.026	115.80
34.800	23	-12.000	12.000	123.800	4.622	4.47
34.800	24	-21.000	12.000	114.800	1.640	0.56
34.800	25	-30.000	90.000	105.800	0.582	0.53

TOTAL AREA (KM**2) = 1039.922
SCF = 0.086

FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION NO.	2. Gov't Accession No.	3. Recipient's Accession No.
	NTIA REPORT 89-243		

4. TITLE AND SUBTITLE
SPECTRUM-CONSERVATION TECHNIQUES FOR FIXED MICROWAVE SYSTEMS

5. Publication Date
May 1989

6. Performing Organization Code

7. AUTHOR(S)
Robert L. Hinkle, Andrew Farrar

8. PERFORMING ORGANIZATION NAME AND ADDRESS
National Telecommunications & Information Administration
Annapolis Office
179 Admiral Cochrane Drive
Annapolis, Maryland 21401

9. Project/Task/Work Unit No.

10. Contract/Grant No.

11. Sponsoring Organization Name and Address
U.S. Department Commerce/NTIA
179 Admiral Cochrane Drive
Annapolis, Maryland 21401

12. Type of Report and Period Covered
Technical Report

13.

14. SUPPLEMENTARY NOTES

15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Since the spectrum is a limited natural resource, the spectrum management community has a major interest in identifying spectrum conservation techniques that will provide more efficient spectrum utilization. Advances in new technology for fixed microwave systems in antennas, modulation schemes and signal processing techniques offer increased efficiency in spectrum utilization. This report analyzes the spectrum conserving properties of the various new technologies for fixed microwave systems applying the concepts in CCIR Report 662-2, and was defined as the spectrum conservation factor (SCF). The report concludes that the SCF technique is an effective indicator of the spectrum conserving properties of technologies which can be used to develop new spectrum standards.

16. Key Words *(Alphabetical order, separated by semicolons)*

Spectrum Efficiency
Spectrum Conservation Factor (SCF)
Fixed Microwave System
7125-8500 MHz Band

17. AVAILABILITY STATEMENT	18. Security Class. *(This report)*	20. Number of pages
☒ UNLIMITED.	UNCLASSIFIED	55
	19. Security Class. *(This page)*	21. Price:
☐ FOR OFFICIAL DISTRIBUTION.	UNCLASSIFIED	N/A

☆ U.S. Government Printing Office: 1980—678-495/529