Approximte existing national radio advertising	1,600,000,000
Estimated growth factor	150%

Estimated anuual national advertising	2,400,000,000
CD Radio Penetration	50%

Available revenues	800,000,000
Number of CD Radio channels	200

Revenue per channel	4,000,000
	============

The potential future revenues available to the CD Radio system users can be even greater. As already pointed out, the advantages of a national radio broadcast will cause businesses marketing their products and services country wide to review overall marketing strategies. This situation will surely expand radio advertising revenues making national radio broadcasting a very profitable venture.

Satellite CD Radio, Inc.
Petition For Rulemaking
May 18, 1990

Appendix 2

Propagation Analysis for Satellite
Sound Broadcasting Systems

APPLICATION OF CODING AND DIVERSITY TO UHF SATELLITE SOUND BROADCASTING SYSTEMS[1]

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ABSTRACT - Sound broadcasting to fixed, portable, and vehicular receivers using transmissions from geostationary satellites has been under study in several countries since the late 1970s. The early studies were undertaken in preparation for the 1979 General World Administrative Radio Conference in anticipation of securing a frequency allocation for the service somewhere in the portion of the radio frequency spectrum extending from 500 MHz to 2000 MHz. These studies assumed the use of analog frequency modulation techniques and simple receivers, assumptions that led to feasible designs for systems that would provide a medium quality service to fixed, portable, or vehicular receivers operating in environments having little shadowing of the line-of-sight propagation path from the satellite. However, link margins of 30 dB or more were required for urban paths experiencing heavy shadowing. With margins of this magnitude, the practicality of a satellite sound broadcasting system was questioned as the required satellite e.i.r.p. increased to over 80 dBW per channel.

This paper presents the results of a study of alternative means by which to reduce the required link margins in a satellite sound broadcasting system, thus improving the economic feasibility of the service and increasing the possibility of sharing a radio frequency allocation with terrestrial services. Propagation models are presented that account for the effects of shadowing and multipath in the operating environments.

Comparisons are made of the performance that results using time, frequency, and space diversity to moderate the effects of shadowing and multipath for vehicular and portable receivers. It is shown that space diversity has the broadest applicability in restoring the channel performance that would otherwise be degraded by Rayleigh fading channels and by quasi-stationary AWGN channels.

The use of space diversity minimizes the effects of Rayleigh fading over the vehicular propagation path in rural, suburban, and urban environments without requiring all receivers to use space diversity in order to receive the sound channel. Thus, a satellite sound broadcasting system designed around the use of space diversity permits the design and manufacture of an assortment of less complex and less expensive consumer receivers containing only those features necessary for proper operation in the environment for which it is intended. Space diversity may easily be applied to vehicular receivers, as well as portable receivers, and used with either simple analog FM systems or with the more complex digital systems.

Example link budgets are given for candidate satellite sound broadcasting system designs that use analog FM and digital modulation techniques. On the basis of the relative satellite transmitter power required and the flexibility required to design a receiver that operates satisfactorily in its intended environment, space diversity provides the most cost-effective means by which to implement a satellite sound broadcasting service that uses either analog FM or digital modulation techniques.

I. INTRODUCTION

There is international interest in developing a satellite sound broadcasting service in which medium- to high-quality sound programs transmitted from a geostationary satellite may be received by the general public possessing consumer quality fixed, portable, and vehicular receivers. Studies assessing the general feasibility of the service, the range of preferred system parameters, and the preferred operating frequency band date back to the early 1960s. The timing of these studies tend to coincide with preparations for international administrative radio conferences that are competent to allocate portions of the spectrum to the service. Suffice it to say that after a series of such conferences, there is yet to be spectrum allocated for satellite sound broadcasting. The latest round of studies began about 1977 in preparation for the 1979 General World Administrative Radio Conference (WARC-79) and has continued as two succeeding conferences have dealt with the issue [1]-[6].

Several administrations submitted proposals concerning satellite sound broadcasting to the WARC-79. The Conference considered these proposals and, though unable to make a suitable allocation to the service, did adopt Resolution 505, which [7]: a) encouraged administrations to carry out sound broadcasting experiments within the band 0.5 GHz to 2.0 GHz; b) requested the CCIR to expedite studies of the technical and operating characteristics of the service and the feasibility of sharing with terrestrial services; and c) authorized the next competent WARC to take appropriate actions regarding an allocation for satellite sound broadcasting, including the possible development and approval of procedures to protect and re-accommodate in other bands assignments to stations in the terrestrial services that may be affected by allocations to a sound broadcasting service.

The 1985 WARC-ORB(1) (a conference concerned with the geostationary satellite orbit and the services utilizing it) was the next competent WARC to consider the satellite sound broadcasting question. It decided that further studies by the CCIR were required and deferred the question of an allocation to the second session of the Conference (WARC-ORB(2)), which was held from 29 August to 5 October 1988.

WARC-ORB(2) considered both the results of the CCIR studies and a proposal submitted by one administration. The Conference decided, in Resolution COM5/1, that the possibility of an allocation to the Broadcasting-Satellite Service (Sound) (BSS (Sound)) should be considered at a future allocations conference dealing with the mobile services (including the mobile-satellite service) and with frequencies in the range 500 MHz to 3000 MHz. This conference will probably be scheduled for 1992. Thus, definitive regulatory action on an international scale must await the next allocations conference.

The technical studies referred to above, plus studies summarized in CCIR Report 955-1 [8] (which is devoted to satellite sound broadcasting), assume the use of analog frequency modulation (FM) sound transmission techniques with characteristics comparable to those used in conventional VHF/FM broadcasting service. Adopting this technology

1. This work was partially supported by the Voice of America.

0018-9316/88/1200-0465$01.00 © 1988 IEEE

permits the reception of satellite sound broadcasts by the addition of a simple, low-cost frequency converter to the front end of a conventional VHF/FM receiver.

'e I (from [8]) provides a summary of the technical and rating characteristics of relatively simple FM satellite sound broadcasting systems required to provide four different grades of service to vehicular receivers. The standard "A" service referred to in the table applies to a rural area with a relatively high elevation angle of 70°. The margin is based on ensuring that the receiver threshold is exceeded over at least 90% of the area.

Standard "B" applies to an urban area receiving at a relatively low elevation angle of 20°. The margin is sufficient to ensure that the vehicular receivers will operate above threshold over 90% of the area.

Standard "C" also applies to reception in an urban area at a relatively low elevation angle. In this case the margin is such that the vehicular receiver will be operating above threshold for 90% of the time over 90% of the area.

Standard "D" also applies to reception in an urban environment except that the margin is set such that the vehicular receiver will be operating above threshold for 90% of the time over 95% of the area.

The studies referenced above have generally concluded that currently available satellite technology is capable of providing a satellite sound broadcasting service given an appropriate ation in a portion of the spectrum extending from about MHz to 3000 MHz. However, as shown in Table I, simple analog FM systems (and by extension, simple digital systems) require a rather high satellite e.i.r.p. to serve reliably the vehicular receiver with only a moderate quality sound broadcasting service. The need for high power increases the cost of the satellite and decreases the possibility of sharing an allocation with terrestrial services. However, the implementation of coding and diversity techniques can mitigate these problems.

The purpose of this paper is to examine the use of coding for digital sound transmission techniques and the use of diversity techniques for both analog FM and digital transmission methods. Using coding and diversity, where appropriate, will [6]:

a) reduce the e.i.r.p. required from the satellite, thus reducing the cost of the satellite,

b) reduce the effects of fading on the sound quality produced by fixed, portable, and vehicular receivers, and,

c) permit reduced spectral power flux density on the surface of the earth, thus facilitating sharing between the BSS (Sound) and terrestrial services.

II. PROPAGATION FACTORS

This section describes the propagation factors affecting the design and performance of the example system designs given in Section V.

Service to receivers in three operating environments are considered in Section V: Case 1) a portable receiver operating inside a house that is not shadowed by trees; Case 2) a vehicle operating in a rural environment that is devoid of significant multipath and shadowing by foliage, and Case 3) a vehicle operating in a rural environment that exhibits significant multipath and shadowing by foliage. Each of these environments exhibits a somewhat different type of propagation path.

A. Fixed and Portable Receiver Propagation Factors

For fixed and portable receivers operated within houses or other types of buildings (Case 1), allowance must be made for absorption and scattering of the signal due to walls, ceilings, and roofs [5]. Measurements of the mean signal within single family dwellings were made at 860 MHz, 1550 MHz, and 2569 MHz using the Application Technology Satellite 6 (ATS-6). These measurements have shown that the penetration loss is a function of frequency, receiving antenna polarization, construction of the house (wood siding or brick veneer), the extent of thermal insulation within the house (ceilings and walls), and the proximity of the room to an outside wall [9]. Penetration loss was found to be virtually independent of elevation angle down to 5 degrees for paths not obstructed by trees or other buildings. The distribution for the penetration loss for each type of house was found to be closely approximated by the normal distribution with a standard deviation (including the random measurement error of about 1.5 dB) of 3 dB.

For the portable radio example analyzed in Section V, it is assumed that the receiver is operated in an inside room of a fully insulated brick veneer house. For an operating frequency of 1000 MHz, the mean penetration loss is 8 dB. To account for the variability in 90% of the houses of this type, an additional 4 dB is added. The resulting 12 dB excess path loss applies to houses of the particular construction assumed, which is assumed not to be shadowed by other buildings or trees. For houses with interior walls and ceilings constructed using gypsum wallboard backed by aluminum foil, the average penetration loss will increase to over 17 dB. Similarly, for houses surrounded by large trees, an additional loss of 12-15 dB at 1000 MHz is appropriate.

B. Vehicular Receiver Propagation Factors

Impairments on the propagation path between the satellite and the vehicular receiver can affect the system performance in a significant way. Early measurements made using ATS-6 [10] indicated that the small-scale variations in the signal power received by a vehicle (i.e., as measured over distances of several hundred wavelengths) could be statistically characterized by the sum of a constant signal and an independent Rayleigh- distributed variate. The probability density function for the envelope of the sum of these variates is given by the well-known Rician distribution. Over a large distance (i.e., a distance in excess of several hundreds of wavelengths) it was found that the distribution of the mean e of the received signal power could be approximated by log-normal density function. The log-normal variate accounted for the mean variation in the line-of-sight (LOS) signal due to foliage and building attenuation; the Rayleigh component accounted primarily for the effects of diffuse scattering from the ground and nearby objects. Recent measurements confirm the general validity of this model [11]-[13].

Propagation data taken at about 800 MHz in a rural area from a simulated satellite-to-mobile link are shown in Figure 1. These data were taken at an elevation angle of 15 degrees along roads with clear LOS paths (curve d) and with paths obstructed by foliage (curve b) [14]. Also shown on the figure are two curves corresponding to the Rayleigh distribution with a 10 dB mean excess path loss (curve a) and the Rayleigh distribution with 0 dB mean excess path loss (curve c). For a lightly shadowed path (curve d), the Rayleigh curve provides a very conservative lower bound on the fading statistics. However, for a heavily shadowed path (curve b), the Rayleigh curve provides a very adequate characterization of the fading statistics. Therefore, the Rayleigh distribution with a suitably selected value for the mean excess path loss provides a practical lower bound on the statistical distribution of the envelope of the received signal.

Based on the discussion above, the channel model used to pare the link budget given in Section V for a portable ceiver operating inside a single story house is the additive white Gaussian noise (AWGN) channel with an excess path loss of 12 dB. Similarly, the link budgets for vehicles operating in a rural environment are based on the Rayleigh fading channel model. For a rural environment that is essentially free from shadowing of the LOS path by trees and other foliage (Case 2), the mean excess path loss is 0 dB. For rural areas with significant LOS shadowing by trees and foliage (Case 3), the mean excess path loss is 10 dB.

III. FORWARD ERROR CORRECTION CODING

The use of forward error correction coding (FEC) affords a means by which to reduce significantly the required e.i.r.p. for digital satellite sound broadcasting systems. Using FEC improves the possibility of deploying a more economical satellite and increases the possibility for sharing an allocation to the BSS (Sound) with terrestrial services. A rate 1/2, constraint length 7 (R=1/2, K=7) convolutional code combined with a decoder using the Viterbi maximum likelihood decoding algorithm (VA) offers a significant coding gain when compared to the performance of an uncoded digital link using quadrature phase shift keying (QPSK) modulation and coherent detection.

omparison of the bit error ratio (BER) for a coded and an oded link is shown in Figure 2. Curve (a) applies to a memoryless Rayleigh fading channel employing an R=1/2, K=7 convolutional code, QPSK with coherent detection, and soft decision decoding using the Viterbi algorithm. Curve (b) is the BER that would be realized over the same link in the absence of coding. As shown in the figure, the code will provide in excess of 36 dB improvement in performance over a memoryless Rayleigh fading channel when compared to an uncoded system at a bit error ratio (BER) of 10^{-5} [15]. This same configuration will provide a coding gain at a BER of 10^{-5} of about 5 dB when compared to an uncoded system over the AWGN channel. Achieving a coding gain of 36 dB using convolutional coding and Viterbi decoding is critical to providing a quality sound program service to the vehicular receiver without requiring excessive e.i.r.p. margins on the link. Coding is not as critical to the performance of the portable receiver. Regardless, the use of a potentially complex Viterbi decoder in a consumer quality receiver is believed to be justified by the availability of several sources for a commercial decoder chip [16]-[18].

IV. DIVERSITY TECHNIQUES

The performance realizable with coding on the fading vehicular channel is dependent on the statistical characteristics of the fading. On channels where the fading rate is much less than the symbol rate, the received signal level is essentially constant for the duration of the symbol. Consequently, the received symbol energy of adjacent symbols will tend to be identical, a condition that does not meet the requirement that the channel be memoryless in order to realize a coding gain of 36 dB. If the channel is not memoryless, there is a catastrophic increase in the BER of high-performance convolutional codes when the channel is in a deep fade. There are three primary diversity techniques capable of lessening the effects of deep fades: 1) frequency diversity, 2) time diversity, and 3) spatial diversity. These methods are briefly described below.

A. Frequency Diversity

Frequency diversity uses M carriers, each carrying the same information, spaced in frequency by an amount that equals or exceeds the coherence bandwidth of the channel. A variation of the frequency diversity technique is being studied by the European Broadcasting Union (EBU) for possible application to a digital satellite sound broadcasting system [19],[20]. The method being studied by the EBU is orthogonal frequency division multiplexing (OFDM) [21], which is essentially a parallel data transmission technique. The approach being implemented by the EBU also uses sub-band coding to achieve a bit rate of 250 kbit/s or less per stereo program, a rate 1/2, constraint length 7 convolutional code, 16 carriers per sound program, and QPSK to modulate each carrier. The symbol rate per carrier is 16.625 kBaud with 250 kHz spacing between carriers belonging to the same program. Fifteen other sound program channels are interleaved with this channel, resulting in a total of 256 carriers spaced 15.625 kHz in a total bandwidth of 4 MHz to transmit 16 sound programs [20].

To obtain independent fading of the carriers with the use of frequency diversity requires that the delay spread of the channel exceed some minimum value. For a channel characterized by an exponential distribution of the delay (typical of a terrestrial path), the mean value of the delay spread must be greater than the reciprocal of the program carrier spacing [22]. If this minimum value is not realized, then fading on the channel will tend towards flat fading, and the a[illegible]l coding gain will be less than expected. For this reason, frequency diversity is most suitable for use in heavily shadowed urban areas where the mean delay spread will be the greatest. The mean delay spread in a rural environment will be less than that of an urban environment. Measurements on a simulated space-to-Earth path in a rural environment indicates that the coherence bandwidth is in excess of 4 MHz (implying a mean delay spread on the order of 0.25 us) [23]. By comparison, the mean delay spread on a terrestrial path in an urban area is on the order of 1.3 us [22]. Consequently the spacing of the carriers used for frequency diversity must be greater in a rural environment.

B. Time Diversity

The second method is based on time diversity. One means by which to implement this technique for a digital system is to interleave the transmitted symbols and to deinterleave the received symbols in a prescribed manner [24]. By introducing a sufficient amount of delay in the interleaver, symbols that were adjacent prior to interleaving are, after interleaving, separated in time by an amount greater than the correlation time of the channel. Performance of a convolutional code is thus restored by separating the symbol error patterns so that symbol errors do not occur in long bursts. This method, which has been studied for application to satellite sound broadcasting [25], is most effective for vehicular channels which exhibit relatively rapid fading. Time diversity requires that an impractical amount of digital memory be installed in the receivers in order to restore the coding gain on channels exhibiting very slow fading. For these reasons, time diversity does not appear to be a practical approach for either a digital system or for an analog FM system.

C. Spatial Diversity

Spatial diversity is based on the use of multiple receiving antennas. The antennas must be spaced sufficiently far apart so that the received signals fade independently. For a terrestrial mobile communication path, the required spacing is on the order of one-half wavelength or greater [22]. Comparable spacings have been found on space-to-Earth paths [10].

The independently fading signals at the output of each antenna may be combined to form an output signal whose fading depth is significantly less than the fading depth of the individual signals. One combining method is maximum-ratio combining. And one implementation of this method uses M phase-locked loops to bring the signals at the output of M antennas into phase coherence. The signals are then amplitude weighted and summed to form a composite signal [22]. Maximal-ratio combining may be used for either digital or analog signals.

For a digital system, the probability of error (P_e) on a Rayleigh fading convolutionally coded link, received with an M-branch spatial diversity, maximal-ratio combining receiver and a Viterbi decoder is given by [15]

$$P_e = \int_0^\infty \frac{\gamma_r^{M-1}\, \varepsilon^{-(\gamma_r/\Gamma)}}{\Gamma^M\,(M-1)!}\, P(\gamma_r)\, d\gamma_r \tag{1}$$

$$P(\gamma_r) = \varepsilon^{(\alpha_o - \alpha_1 \gamma_r)}\quad,\ \gamma_r > \frac{\ln(2) + \alpha_o}{\alpha_1} \tag{2a}$$

$$P(\gamma_r) = 1/2 \quad,\ \gamma_r < \frac{\ln(2) + \alpha_o}{\alpha_1} \tag{2b}$$

$$\alpha_o = 4.4514 \tag{3a}$$

$$\alpha_1 = 5.7230 \tag{3b}$$

where,

γ_r = instantaneous bit-energy-to-noise density ratio (numeric),

M = order of diversity, and,

Γ = mean branch bit-energy-to-noise density ratio (numeric).

Equation (2) applies specifically to an optimal R=1/2, K=7 convolutional code [26].

Equation (1) has been evaluated with the results shown in Figure 3. Curve (a) of the figure shows the BER for 4th order spatial diversity with maximal-ratio combining. It is seen that 4th order diversity with a mean bit-energy-to-noise density ratio per branch of about 7.0 dB achieves a BER=10^{-5}. This value is used in the link budget for the example vehicular receiver in Section V.

Figure 3 also shows the BER for an R=1/2, K=7 convolutional code received over an AWGN channel (curve b) and over a memoryless Rayleigh fading channel (curve c). Coherent detection of a QPSK carrier in combination with VA decoding was assumed in both cases.

Spatial diversity with maximal-ratio combining may also be used for satellite sound broadcasting systems employing analog FM modulation techniques. In a Rayleigh fading environment, the probability density function of the instantaneous received carrier power relative to the mean carrier power per branch for an M-branch maximal-ratio combiner is given by [22]

$$P(\gamma) = \frac{1}{(M-1)!}\,\frac{\gamma^{M-1}}{\Gamma^M}\,\varepsilon^{(-\gamma/\Gamma)} \tag{4}$$

and the probability distribution function for the M-branch combiner is given by

$$P(\gamma \le X) = 1 - \varepsilon^{(-X/\Gamma)} \sum_{k=1}^{M} \frac{(X/\Gamma)^{k-1}}{(k-1)!} \tag{5}$$

where,

γ = the instantaneous carrier power at the output of the combiner (numeric),

M = order of diversity, and,

Γ = mean carrier power per branch (numeric).

Equation (5) is plotted in Figure 4 for M=1 to M=4. The figure illustrates the reduction of the fading depth of the received carrier power, at a prescribed probability, for an M-branch spatial diversity and maximal-ratio combining. As illustrated in the figure, the improvement is about 26 dB at the 0.001 probability level for a 4-branch system when compared to no diversity in a Rayleigh fading environment.

V. EXAMPLE SYSTEMS

Two example satellite sound broadcasting systems have been considered: 1) a digital system capable of providing a high-quality service, and 2) an analog FM system capable of providing a medium quality service.

The example link calculations given in Tables II and III assume a somewhat higher receiving antenna gain and a lower receiving antenna system noise temperature than the values assumed in Table I. Further, the link calculations are based on an operating frequency of 1000 MHz in order to be consistent with example systems described in the literature. The results may, however, be easily scaled to other operating frequencies ıe range 500 MHz to 3000 MHz.

A. Digital System (Case 1)

The significant characteristics of an example digital satellite sound broadcasting system are given in Table II. Adaptive delta modulation (ADM) has been selected in view of: 1) the performance achieved at moderate sampling rates and channel error rates, and 2) the availability of a low cost decoder chip set [27]. At a bit rate of 220 kbit/s per stereo sound channel (440 kbit/s for a stereo program channel), ADM achieves a measured signal-to-noise ratio (SNR) of at least 58 dB in a 15 kHz baseband and a dynamic range of 85 dB [28]. Subjectively, a BER less than 10^{-5} corresponds to an impairment rating greater than 4.5 on a 5.0 point scale. (An impairment rating of 4 indicates a perceptible, but not annoying, degradation in the sound quality, whereas an impairment rating of 5 indicates an imperceptible degradation in the sound quality [29].)

An R=1/2, K=7 convolutional code is used for FEC in conjunction with QPSK and coherent demodulation at the receiver.

The performance given in Table II for the portable receiver operating inside a house is based on the assumption that a VA decoder is used. It should be noted however that it is not ıolutely necessary that a VA decoder be included in all ıable receivers. For example, a home receiver with an outdoor antenna would need only a simple decoder that should cost less than a receiver with a VA decoder.

The vehicular receiver is potentially the most complex receiver since it must operate in the most difficult environment. The performance given in Table II is based on the use of quad-spatial diversity (four receiving antennas spaced a half-wavelength or more apart), maximal-ratio combining, and a full implementation of a decoder using the Viterbi maximum likelihood algorithm.

From the results given in Table II, it is seen that the use of ADM and convolutional coding provides a very high (Q=4.5) sound quality as received by fixed, portable, and vehicular receivers operating in a satellite sound broadcasting system. Reference to Table I will show that this performance is achieved at a lower e.i.r.p. and lower spectral power flux density than previously studied FM systems [1]-[6]. Thus, the possibility of sharing between the BSS (Sound) and terrestrial services should be enhanced. Further, the economic feasibility of satellite sound broadcasting is improved since a lower per channel e.i.r.p. is required. This will generally mean that the space segment investment cost for a coded ADM system will be less than that for a comparable FM or uncoded digital system.

B. Analog FM System (Case 2)

The link budget for an example analog FM system is shown in Table III. Service is to a vehicular receiver operating in a lightly shadowed and also in a heavily shadowed rural area. The receiving system uses quad-spatial diversity and maximal-ratio combining to minimize the effects of Rayleigh fading. An operating margin of 3.5 dB above a 10 dB threshold has been used which corresponds to a probability of 0.001 that the signal will fade below the threshold. (Listening tests are needed to verify the suitability of this margin.)

Comparing the general results given in Table I with those given in Table III shows that quad-spatial diversity with maximal-ratio combining provides a significant means to reduce the satellite e.i.r.p. required to adequately serve a vehicular receiver. A reduction of over 26 dB is possible based on the criterion that the probability of fading below threshold must be less than 0.001 in a Rayleigh fading environment.

VI. SUMMARY AND CONCLUSIONS

The vehicular receiver operating in an environment in which the space-to-Earth propagation path is characterized as a heavily shadowed Rayleigh fading channel imposes the most severe requirements on the design of a satellite sound broadcasting system. In prior studies, these conditions have been accounted for by either adding large link margins or by using channel coding methods that require a high level of complexity to be built into all receivers, regardless of the environment in which they are intended to operate. The consequence of using this approach has resulted either in the need for satellites with excessive e.i.r.p. (which increases the cost and risk associated with the service) or in the imposition of a high level of receiver complexity. In order to advance the commercial feasibility of a satellite sound broadcasting service, it would be desirable to minimize the e.i.r.p. required from the satellite (to reduce cost and risk) and to enable the use of receivers of varying cost and having a level of complexity commensurate with the environment in which they are intended to operate.

It has been shown that the use of quad-spatial diversity with maximal-ratio combining in the vehicular receiver permits a significant reduction in the satellite e.i.r.p. for both digital and analog FM systems. A further reduction is possible with digital systems through the use of an R=1/2, K=7 convolutional code.

It may be pointed out that the system concepts based on the use of quad-spatial diversity and maximal-ratio combining afford the possibility of a range of modular receiver designs. It is further contended that a modular design offers the best opportunity to market cost effective, consumer quality receivers tailored to the particular operating conditions.

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TABLE I

LINK BUDGET FOR A UHF ANALOG FM
SATELLITE SOUND BROADCASTING SYSTEM [8].

System parameter	Standard of service			
	A	B	C	D
Type of modulation	FM			
Carrier deviation (kHz)	±75			
Noise bandwidth (kHz)	250			
Carrier-to-noise ratio (dB)	10			
Coupling loss (dB)	1			
Receive antenna gain (dBi)	3			
Receive system noise temp.(K)	2000			
Carrier frequency (MHz)	1000			
Link margin (dB)	6	15	25	33
LOS pfd at beam edge (dB(W/m^2)	-106.4	-97.4	-87.4	-79.4
Equivalent field strength at beam edge (dB(uV/m))	39.4	48.4	58.4	66.4
Maximum spreading loss (δ=17 deg.) (dB/m^2)	-163.0	-163.0	-163.0	-163.0
Beam-center e.i.r.p. (dB(W))	59.6	68.6	78.6	86.6
Satellite antenna gain (D=20 m) for 1 deg. BW (dBi)	43.9	43.9	43.9	43.9
Antenna input power (dB(W))	15.7	24.7	34.7	42.7
Antenna input power (W)	37	295	2951	18621

TABLE II

LINK BUDGET FOR A DIGITAL SATELLITE SOUND BROADCASTING SYSTEM USING CONVOLUTIONAL CODING, VA DECODING, AND QUAD-SPATIAL DIVERSITY ON THE VEHICLE.

System parameter	Value
Type of modulation	QPSK
Primary reception mode	stereophonic
Bit rate (kbit/s)	440
Code rate	1/2
Modulation rate (kBaud)	440
Required RF Bandwidth (kHz)	880
Received SNR (dB)	58
Subjective sound impairment	Q=4.5
Received bit error ratio	10^{-5}
Audio bandwidth (kHz)	15
Carrier frequency (MHz)	1000

Receiving environment	Vehicular		House
	Light foliage	Heavy foliage	
Receiver antenna gain (dBi)	5.0	5.0	5.0
Coupling loss (dB)	1.0	1.0	1.0
Receiver system noise temp. (K)	600	600	600
Required E_b/N_o (dB)	7.0	7.0	3.8
Implementation margin (dB)	1.0	1.0	1.0
Mean excess path loss (dB)	0	10.0	12.0
LOS pfd at beam edge (dB(W/m^2)	-119.0	-109.0	-110.2
Equivalent field strength at beam edge (dB(uV/m))	26.8	36.8	35.6
Maximum beam-center pfd per 4 kHz (dB(W/m^2/4kHz))	-136.1	-126.1	-127.3
Maximum spreading loss (δ=17 deg.) (dB/m^2)	-163.0	-163.0	-163.0
Beam-center e.i.r.p. (dBW)	47.0	57.0	55.8
Satellite antenna gain (D=20 m) for 1 deg. BW (dBi)	43.9	43.9	43.9
Antenna input power (dB(W))	3.1	13.1	11.9
Antenna input power (W)	2.0	20.4	15.5

TABLE III

LINK BUDGET FOR AN ANALOG FM SATELLITE SOUND BROADCASTING SYSTEM SERVING A VEHICULAR RECEIVER USING QUAD-SPATIAL DIVERSITY AND MAXIMAL RATIO COMBINING.

System parameters	Value	
Type of modulation	FM	
Primary reception mode	Monophonic	
Carrier deviation (kHz)	± 75	
Noise bandwidth (kHz)	250	
Carrier-to-noise ratio (dB)	10.0	
Signal-to-noise ratio (dB)	40.0	
Coupling loss (dB)	1.0	
Receiver antenna gain (dBi)	5.0	
Receiver system noise temperature (K)	600	
Carrier frequency (MHz)	1000	
Probability of fading below threshold	0.001	
Margin above 10 dB threshold (dB)	3.5	
Receiving environment	Light foliage	Heavy foliage
Mean excess path loss (dB)	0	10.0
LOS pfd at edge of beam (dB(W/m^2))	-115.9	-105.9
Equivalent field strength (dB(uV/m))	29.9	39.9
Maximum beam-center pfd per 4 kHz (no energy dispersal) (dB(W/m^2/4 kHz))	-115.9	-105.9
Maximum spreading loss (δ=17 deg.) (dB/m^2)	-163.0	
Beam-center e.i.r.p. (dBW)	50.1	60.1
Satellite antenna gain (D=20 m) for 1 degree beamwidth (dBi)	43.9	
Antenna input power (dBW)	6.2	16.2
Antenna input power (W)	4.2	41.7

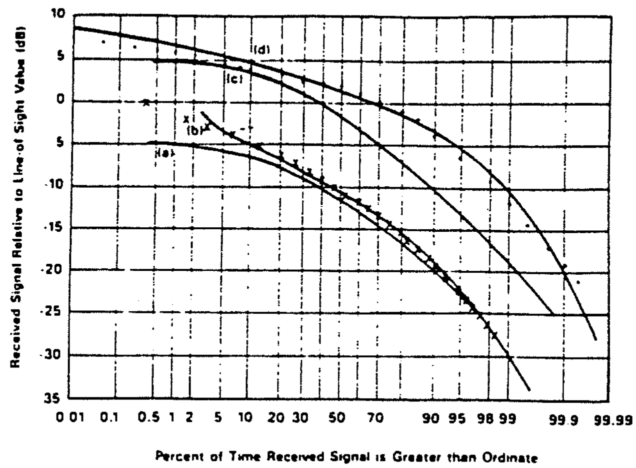

Fig. 1. Measured and calculated probability distribution for the envelope of the received signal. Curve (a) is a Rayleigh distribution with 10 dB excess path loss, curve (b) is the measured distribution in a heavily shadowed rural environment, curve (c) is a Rayleigh distribution with 0 dB mean excess path loss, and curve (d) is the measured distribution in a lightly shadowed rural environment [14].

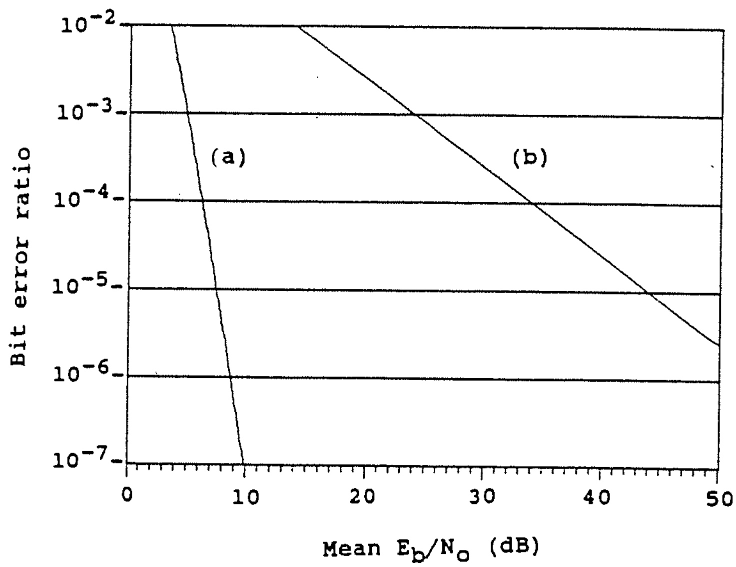

Fig. 2. Performance of coded and uncoded QPSK with coherent detection over a memoryless Rayleigh fading channel. Curve (a) $R=1/2$, $K=7$ convolutional code with VA soft-decision decoding, and curve (b) uncoded.

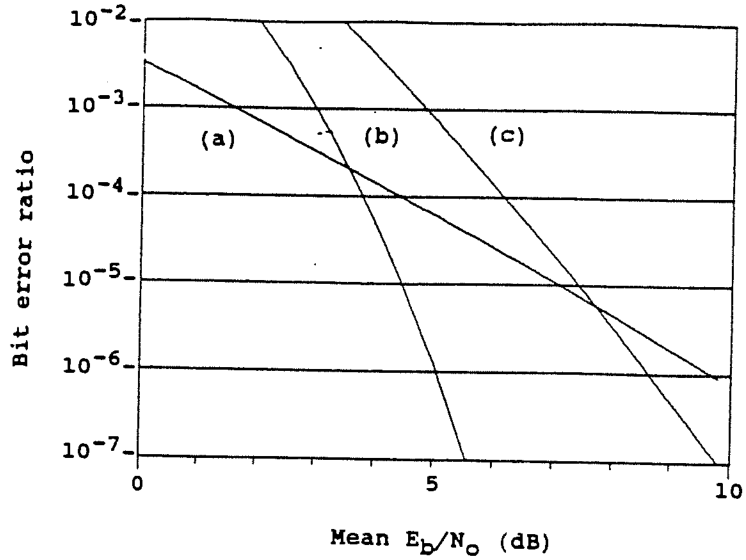

Fig. 3. BER for soft-decision VA decoding of convolutional code; using quad-spatial diversity with maximal-ratio combining on a Rayleigh fading channel with memory (curve (a)), on an AWGN channel (curve (b)), and on a memoryless Rayleigh fading channel (curve (c)).

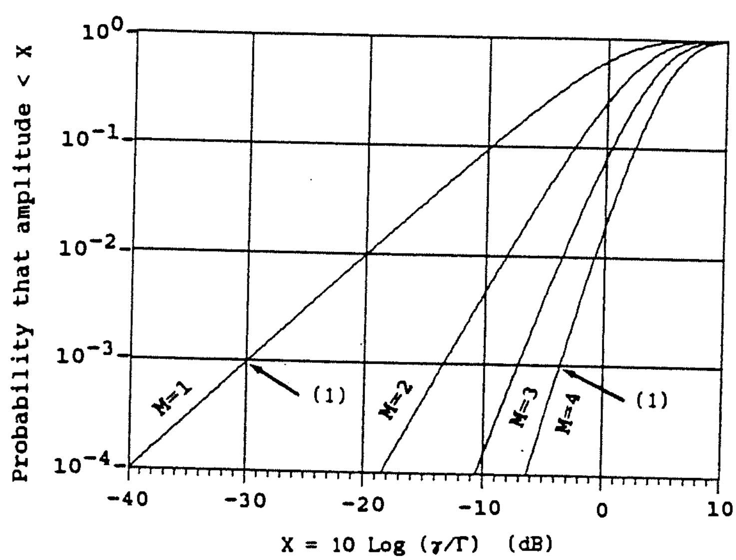

Fig. 4. Performance curves for maximal-ratio combining of independently fading signals. (1) see text.

Appendix 3

CCIR Report 955-1 (MOD F)
"Satellite Sound Broadcasting With
Portable Receivers and Receivers
In Automobiles"

CCIR
XVIIth Plenary Assembly
Düsseldorf, 1990

Document 10-11S/1011-E
15 January 1990

Ref: Document 10-11S/214 Rev. 1

REPORT 955-1 (MOD F)*

SATELLITE SOUND BROADCASTING WITH PORTABLE RECEIVERS AND RECEIVERS IN AUTOMOBILES

(Question 2/10 and 11, Study Programmes 2B/10 and 11, 2K/10 and 11)

(1982-1986)

This report contains:

* This Report should be brought to the attention of Study Groups 5, 6 and 8.

In the case of an FM model, the quality objective at the edge of the coverage area is taken as a subjective quality corresponding to grade 3 on the 5 point CCIR quality scale. This corresponds to a weighted signal-to-noise ratio (S/N) of 40 dB. As a second condition to be met, the carrier-to-noise ratio (C/N) needs to be kept above the FM threshold (10 dB). The interference protection ratios should be high enough to ensure that the system noise is the factor controlling the system availability.

In the case of a digital model, the quality objective at the edge of the coverage area is equivalent to a subjective quality of grade 4 on the 5 point CCIR quality scale. This will translate into an allowed bit error-ratio depending on the type of source coding used and on the level of protection against errors, and will translate into a required carrier-to-noise ratio depending on the channel coding used. In this case, interference is considered as additive noise and the protection ratios can be set such that the noise contribution from the co-channel interference is 1 dB and each adjacent channel contributes 0.5 dB.

For the advanced digital systems the objective is to provide high quality stereophonic service with fixed, portable and mobile receivers.

2.2 *Suitable modulation methods*

Studies performed by several administrations demonstrate in principle the technical feasibility of sound broadcasting from geostationary satellites using antennas large enough (e.g. 8 to 20 m diameter at 1 GHz) to provide national coverage, and designed for reception with low-cost portable domestic receivers, receivers installed in automobiles and permanently installed receivers. In the first two cases, the receiving antenna would be small and would have limited directivity.

Three types of systems have been studied to date. The first uses frequency modulation with parameters compatible with terrestrial FM broadcasting, this first type includes also the companded FM system which would not be compatible with present FM receivers. The second type assumes simple digital modulation. The third type is also digital, but it uses a series of advanced techniques to reduce the bit-rate and, above all, to guarantee reception in the presence of fading caused by multi-path propagation.

2.2.1 FM system

The FM model would enable monophonic reception in the case of portable and mobile receivers using small antennas with limited directivity, and stereophonic reception in the case of permanent installations where obstructions can be minimized and larger antennas can be used. In such a case, the receiver could be identical to those available on the current market, with a simple addition (or exchange) of the freqeuncy converter at the input stage.

The same carrier deviation and the same pre-emphasis are assumed as well as the same stareophonic multiplex. Preliminary analyses tend to show that these modulation parameters are close to optimum in terms of minimizing the required satellite power and optimizing the spectrum usage.

A number of administrations attach great importance to the use of existing FM receivers for the broadcasting-satellite service with the possibility of a quality similar to that offered by terrestrial VHF/FM services.

Some modifications to the parameters could offer advantages. By way of example, a system is shown that has 10 kHz audio bandwidth and uses companding to permit a reduction of the deviation.

2.2.2 Simple digital system

The second modulation technique assumes a digital source coding similar to one of the systems suggested in Report 953 for a near-instantaneous companded 15 kHz high quality monophonic sound channel. Error protection is provided on the range code and error concealment on samples resulting in a total bit rate of 338 kbit/s. A channel coding in the family of 4-PSK with differential demodulation (e.g. DMSK, 2-4 PSK, TFM...) was assumed with the following characteristics in mind: spectrum efficient coding, ruggedness against channel non-linearity and demodulator simplicity for low cost implementation with minimum margin with respect to the theoretical performance. The minimum level of signal quality ($Q = 4$) is found to be achievable at a bit error ratio of 10^{-3} with a channel bandwidth equivalent to the bit rate and with a C/N of 9 dB including the implementation margin (see Annex I of Report 632).

An alternative to 4-PSK which has similar spectral characteristics, but which may offer the possibility of more economic receivers, is VSB/2-PSK [Pommier and Veillard, 1979].

In the case of simple digital modulation, the model has been based on monophony. Stereophony would require a second channel or a doubling of the bit rate but stereophonic reception would then be possible in the same reception conditions as the monophonic reception. In addition, any digital system also has a large flexibility to accommodate different types of facilities such as the number and quality of channels and data broadcasting.

Report 953 also describes a source coding method based on adaptive delta modulation which may allow adequate audio quality to be obtained at a somewhat lower bit rate.

Current developments in digital sound and data systems indicate that they are now becoming economically attractive to the mass consumer market and the inherent flexibility of signal options which may be readily built into these systems may make them become more attractive than FM systems.

2.2.3 Advanced digital systems

Advanced digital systems can overcome the problems caused by obstruction effects and the presence of multipath propagation which results from specular or diffuse reflections. This occurs on roads in rural areas where the path passes through foliage and in urban areas where there are numerous obstacles. When the fading has Rayleigh distribution (see Annex II) and is frequency-selective, the error rate of a simple digital system cannot fall below an acceptable limit, so the resulting poor quality cannot be improved by increasing either the link margin or the satellite power [CCIR, 1986-90a, b]. The effects of frequency selectivity can be overcome through the use of symbol durations which are large with respect to the dispersion of the echo delays, which limits the bit-rate per carrier [CCIR, 1986-90b, c]. A powerful channel coding mechanism can then be applied (convolutional code with Viterbi decoding), but it is necessary to ensure the independence between successive symbols with respect to channel fades. This is achieved by interleaving the symbols either in time or in frequency (the total bit rate is thereby distributed between several carriers spaced sufficiently far apart in frequency [Pommier and Yi Wu, 1986]. Temporal interleaving is effective, however, only if the receiver is mounted in a vehicle travelling above a certain speed. If the receiver is stationary, frequency interleaving must be used or, alternatively, space diversity reception [Miller, 1987], [CCIR, 1986-90d]. When frequency interleaving is used, carriers modulated with other sound channels may be placed between those carrying the parts of a given channel, using orthogonal frequency division multiplexing (OFDM) [Alard and Lassalle, 1987]. Finally certain proposals for advanced digital systems involve the use of a source coding offering powerful bit-rate reduction (e.g., sub-band coding); with this technique the bit-rate is barely 220 kbit/s for one high-quality stereophonic programme. Further details on advanced digital systems are given in Annexes III and IV.

2.3 *Suitable frequency bands*

Such a system is feasible in a frequency band in the vicinity of 1 GHz. The lower and upper frequency limits are dictated by the following considerations:

- for the lower limit (around 500 MHz):
  - the man-made noise increases proportionally with decreasing frequency;
  - the diameter of the satellite transmit antenna increases proportionally with decreasing frequency;
- for the upper limit (around 2 GHz):
  - the effective area of the receive antenna which is necessary for such a system diminishes with increasing frequency; this entails an increase in satellite transmit power in proportion of the square of the frequency.

All the examples of the present report assume a carrier frequency of 1 GHz. It is considered as non-economic to increase the satellite power by more than 6 dB which, according to the law of the square of frequency, leads to a maximum frequency of 2 GHz. In addition, however, the frequency also affects to some extent the link margin needed for a given service quality. For instance, experiments at 1 500 MHz [Guilbeau, 1982] have suggested that the link margin in an urban area increases from 15 dB to 18 dB for 20° elevation, when considering the case B defined in section 2.6.3.3

In Resolution 520, WARC ORB-88 extended the possible frequency range for the broadcasting-satellite service (sound) to 3 GHz.

Table I shows a comparison of the satellite power required at 0.5, 1, 2 and 3 GHz, taking as a reference the link budget for the advanced digital system II, code A at 1 GHz (see Table VI, §2.6.4.5). The link margins at 2 and 3 GHz are based on a conservative extrapolation of the propagation data currently available for Europe. This data is subject to further experimental studies.

TABLE I - *Comparison of the satellite power required at 0.5, 1, 2 and 3 GHz*

Frequency (GHz)		0.5	1.0	2.0	3.0
Increase of power due to f^2 law (dB)		-6	0	6	9.5
Increase of link margin (dB)		-2	0	3	5
Satellite antenna input power for one stereophonic programme in a 1° beam	(dBW)	4.9	12.9	21.9	27.4
	(W)	3.1	19.5	154.9	549.5
Total satellite antenna input power for 16 programmes	(W)	49.4	311.0	2478.0	8793.0

It is seen from Table I, which neglects some other secondary factors like the coupling loss and the receiver noise temperature, that a system operating at 2 GHz requires a satellite power which is roughly 8 times higher than at 1 GHz; at 3 GHz, the required power is roughly 30 times higher than at 1 GHz; at 0.5 GHz, the required power is however about 6.3 times lower than at 1 GHz.

It should be noted that the same considerations as regards the effect of frequency apply to other modulation schemes, such as conventional or companded FM and simple digital modulation. Also, sharing difficulties may be exacerbated at higher frequencies due to high link margins required.

2.4 Satellite transmitting antenna

Studies summarized in this report have consistently assumed a reflector or similar physical aperture type transmitting antenna (as opposed to wire-type antennas) with a 3 dB beamwidth of 1°. This suggests that technology studies of physical aperture type antennas for 12 GHz satellite transmitting applications may, upon extrapolation of the physical dimensions of the antenna to the new operating frequency, be applicable to the satellite sound broadcasting application in Band 9. In particular, the satellite antenna diagrams used at WARC-77 are considered to be feasible in Band 9 [CCIR, 1986-90e]. Further details are given in Annex I.

2.5 Alternative satellite orbits

The link budget examples below are all derived assuming the use of a geostationary satellite, where it can be seen that the link margin increases substantially as the elevation angle decreases. Some preliminary studies (J.H. Stott, 1985; FTZ, 1986; ESA, 1988) have been made on the possible use of highly-elliptical orbit to alleviate this effect.

Examples of such orbits are those inclined at an angle of 63.43° with periods of either 12 hours ("Molniya") or 24 hours ("Tundra") arranged such that the satellite appears to be almost directly over the target coverage area for a significant part of its orbit period. This has the advantage for medium to high latitude countries of maintaining a high elevation angle at the receiver with the result that both shadow-loss and multipath may be greatly reduced. In addition, it is possible to take advantage of the constantly high elevation value to increase the antenna gain of the mobile.

Consequently, satellite power requirements would be similarly reduced, giving a considerable easement of both inter- and intra-service sharing constraints. This would lead to more efficient spectrum planning with mixed use of geostationary and non-geostationary satellite orbits as appropriate to the coverage areas.

The major differences between geostationary and non-geostationary systems are that the latter comprise either two ("Tundra" orbit) or three ("Molniya" orbit) satellites in differently phased orbits which are required to provide 24 hour service. Additional factors, such as launch and orbiting spares arrangements, Doppler correction and satellite hand-over strategies, variation of coverage and radiation hardening, at least for "Molniya" orbits, to protect the payload from damage on repeatedly passing through the Van Allen radiation belts need to be considered. Further details are given in draft Report AD/8, but further study is required to quantify the balance of advantages and disadvantages and determine the relative economics of geostationary and non-geostationary approaches for the BSS (sound).

2.6 *Link budget*

2.6.1 *Carrier-to-noise ratio*

A value of C/N of 10 dB representing the FM threshold will give an audio frequency signal-to-noise ratio, with the modulation parameters indicated, of about 40 dB (CCIR quasi peak), weighted, in the case of 50 µs pre-emphasis, or a slightly higher value for 75 µs pre-emphasis.

The C/N objective for the digital system includes 1 dB equivalent additive noise from co-channel interference and 0.5 dB from each one of the two adjacent channels. The noise performance for the digital system is given in terms of subjective quality (4 = good).

For the advanced digital systems, the objective is defined in terms of the E_b/N_o ratio needed for a specified error-ratio, where E_b denotes the average energy received for useful bits of information and N_o the noise spectral power density.

2.6.2 *Receiving antennas*

Receiving antennas for stationary, portable, and vehicular applications are discussed in this section.

Stationary receiving antennas

In fixed locations such as houses, apartment buildings, and commercial buildings it is feasible to provide a higher service quality by using fixed outdoor antennas exhibiting a higher gain (e.g., about 15 dB) than might be used on portable and vehicular receivers. A helix is an example of a suitable type antenna.

Portable receiving antennas

The use of simple antennas such as a crossed-dipole, cavity-backed dipole, and slotted dipoles exhibiting a gain in the range of 3 dBi to 5 dBi has generally been assumed in the studies.

Vehicular receiving antennas

Vehicular receiving antennas play an important role in determining sharing possibilities and system cost in satellite sound broadcasting systems. Simply stated, the greater the vehicular receiving antenna gain, the lower the satellite per-channel e.i.r.p. Studies to date have generally assumed the vehicular receiving antenna to have a gain on the order of 5 dBi. However, work is currently under way [Ball Aerospace, 1984, 1985; Cubic Corp. 1984, 1985] to develop circularly polarized, steered array antennas with gains of the order of 6-12 dBi suitable for use on automobiles, vans, and trucks. This work may have applicability to satellite sound broadcasting systems for specific applications [CCIR, 1986-90f].

Mechanically and electronically steered rooftop antennas have been studied. They provide reasonable gains at mid to high latitudes, and suppress ground reflections to minimize multipath fading. Medium gain (6-12 dBi) steerable vehicular antennas may be a viable alternative to low gain omnidirectional vehicular antennas. The implied additional expense in using a steerable antenna may be offset by lower e.i.r.p. from the satellite, by the enhanced possibility of sharing with other services, and by improved orbit-spectrum utilization.

2.6.3 Propagation aspects

The design, and as a consequence the cost of a satellite sound broadcasting system, is strongly dependent on the factors affecting the propagation characteristics on the space-to-Earth path to the vehicular receiver in particular, and generally to a lesser extent to the portable receiver. The propagation path is subject to attenuation by shadowing due to buildings, trees, and other foliage; and to multipath fading due to diffuse scattering from the ground and nearby obstacles such as trees and buildings. The degree of impairment to the received signal level depends on the operating frequency, the elevation angle to the satellite, and the type of environment in which the receiver is operating: whether it is an open, rural, wooded or mountainous, suburban or dense urban environment.

2.6.3.1 Propagation models

For moderate satellite elevation angles, it is known (see Annex II) that over large areas (of the order of several hundred wavelengths), the mean value of the field strength follows a log-normal distribution. However, within small areas (of the order of a few wavelengths), two distribution models may be applied:

- Rayleigh distribution where there is no direct line-of-sight to the satellite; or
- Rice distribution where there is direct line-of-sight to the satellite; giving one component of constant amplitude.

Although the presence of waves with constant amplitude applies to a large number of receiving locations, the Rayleigh model, which is the least favourable, cannot be ignored since it is applicable in many urban areas.

Results of recent measurements [Loo, 1985], [Jongejeans, *et al*, 1986] and [Lutz et al, 1986] suggest that for the purpose of analyzing the performance of advanced digital satellite sound broadcasting systems using forward error correction coding, that the satellite-to-vehicular propagation path may be modeled as a Rayleigh fading channel with a mean excess path loss dependent on the type of operating environment.

Four different propagation paths are considered:

- a portable receiver operating inside a house that is not shadowed by trees;
- a vehicle operating in a rural environment devoid of significant multipath and shadowing by foliage;
- a vehicle operating in a rural or suburban environment with some multipath and shadowing by trees and foliage; and
- a vehicle operating in a dense urban environment with significant multipath from nearby buildings, cars and other objects.

In general, the UHF satellite propagation path is characterized by shadowing and by the presence of multiple reflected paths. The channel can be frequency selective or non-selective depending on the relationship between the delay spread of the reflected waves and the channel bandwidth. The values associated with the delay spread will be minimal in rural areas, and will be progressively larger in suburban and urban areas. Measurements made at 910 MHZ in a rural area on a simulated space-to-Earth path indicate that the delay spread is predominantly less than 1 μs and is primarily due to reflection and scattering from the trunks of trees [Bultitude, 1987].

Comparable results with somewhat larger delay spreads may be anticipated for the space-to-Earth paths in an urban environment. The multipath propagation characteristics of the satellite channel are usually described in terms of the multipath delay spread and correlation bandwidth. The delay spread T_o is a measure of the duration of an average power delay profile of the channel. The correlation bandwidth B_c is the bandwidth at which the correlation coefficient between two spectral components of the transmitted signal takes a certain value, say 90%. The empirical relationship between the correlation bandwidth at 90% correlation and the delay spread is given in section 4 of Annex II.

Considering a simple digital modulation system operating in a frequency selective channel, the error performance is dependent upon the spread of delays introduced by the different paths, as well as by the amplitude of the component signals. Assuming that each wave is affected by a multiplicative Rayleigh process [Pommier and Wu, 1986], with an exponential distribution of delays of standard deviation, T_o, a level of intersymbol interference will be introduced which depends upon the delay-spread to the symbol-period ratio, T_r (i.e., the ratio, T_o/T, where T is the duration of the modulation symbol).

2.6.3.2 Mitigation techniques

The use of diversity techniques on the vehicular receiver can significantly improve the performance of the receiver when operating in a heavily shadowed, Rayleigh fading environment. There are three primary diversity techniques: 1) frequency diversity, 2) time diversity and 3) spatial diversity [Proakis, 1983]. Each of these techniques may be used with systems employing digital modulation methods. However, for systems employing frequency modulation, spatial diversity is the most practical fading mitigation technique [Miller, 1988]. These diversity methods are briefly described below.

2.6.3.2.1 Frequency diversity

Frequency diversity uses a number of carriers spaced in frequency by an amount that equals or exceeds the correlation bandwidth of the channel. Spectrum efficiency is retained by frequency interleaving a number of separate programme channels to completely fill the frequency band. Spectrum occupancy can be maximized by the use of overlapping orthogonal carriers. Independent fading of the carriers requires that the delay spread of the channel exceed some minimum value. For a channel characterized by an exponential distribution of the delay (typical of a terrestrial path), the mean value of the delay spread must typically be greater than the reciprocal of the programme carrier spacing. In the case of the system described in Annex IV, however, the condition that applied is simply that the total channel bandwidth has to be at least twice the reciprocal of the mean value of the channel delay spread. When this condition is met (independent, frequency selective, Rayleigh fading), a reduction in the link margin of up to 36 dB is possible for a digital system under ideal conditions.

Because of this dependence on delay spread, frequency diversity is most suitable for use in heavily shadowed urban areas where the mean delay spread will be the greatest and independent fading (selective fading) of adjacent carriers may be assured. In rural environments, the delay spread is sometimes too small to provide a narrow enough correlation bandwidth, then the fading on the channel will tend towards flat fading and the actual coding gain will be less than expected. If such a situation occurs, an efficient mitigation technique is either the combination of frequency and time diversity or the use of space diversity. A system based on the use of frequency and time diversity is described in Annex IV.

2.6.3.2.2 *Time diversity*

Time diversity is a technique that is most suitable for use with digital transmission methods. It requires an orderly scrambling of the data symbols prior to transmission and the restoration of the order at the output of the receiver. The introduction of the orderly scrambling and descrambling transforms a burst of errors that occurs during a deep fade into random errors. The use of time diversity combined with forward error correction coding will restore the performance of forward error correction codes by transforming the burst error channel caused by shadowing and Rayleigh fading into a random error channel. Ideally, a reduction in the link margin of up to 36 dB is possible.

The principal disadvantages of time diversity are: the need for all receivers to incorporate the descrambling circuitry (primarily memory chips); poor performance at vehicle speeds lower than the system design, and practical signal processing considerations which limit application to digital modulation methods. Annex III describes the design and performance of a system based on the use of time diversity.

2.6.3.2.3 *Spatial diversity*

Spatial diversity is based on the use of multiple receiving antennas which are spaced sufficiently far apart so that the received signals fade independently. The independently fading signals at the output of each antenna are then combined to form an output signal whose fading depth is significantly less than the fading depth of the individual signals. One combining method is maximum-ratio combining. One implementation of this method uses M phase-locked loops to bring the signals at the output of M antennas into phase coherence. The signals are then amplitude weighted and summed to form a composite signal. Quad-diversity with maximal-ratio combining in a Rayleigh fading environment will permit a 36 dB reduction in the link margin for a digital system under ideal conditions.

For an analogue FM system, a 26 dB reduction in the depth of a fade at the 0.001 probability value may be achieved with quad-diversity and maximal-ratio combining [Miller, 1988]. The advantages of spatial diversity are: applicable to both analogue FM and digital systems, and, it does not impose complexity on all receivers, only on those (vehicular receivers) which need the added performance afforded by the use of spatial diversity. The disadvantage of spatial diversity is the need for multiple antennas on the vehicle associated with a set of several interdependent phase locked loops. Additional studies are needed to fully evaluate the effectiveness of spatial diversity when applied to FM and digital systems particularly in urban environments.

2.6.3.3 Link margins

Several values of link margin have been assumed in the following table. These are estimates of the allowances required in the various cases listed below. Further discussion of this problem is given in Annex II.

Case A: In this case a margin of 6 dB is used. This should give a *C/N* of at least 10 dB for 90% of receiving points in a rural area, and for an angle of elevation of the satellite exceeding 70°, corresponding to a service in low-latitude areas. Mobile reception on roads in these circumstances should be satisfactory, i.e. above threshold, except when close to tall obstructions that would be obvious to the listener.

Case B: The 15 dB margin covers the case of Annex I, namely reception in an urban area, for 20° angle of elevation of the satellite (high-latitude country) and to a service quality corresponding to a $C/N > 10$ dB at 90% of sites [Guilbeau, 1979].

Case C: The 25 dB margin covers the case of reception in urban areas where 90% of areas are served in such a way that 90% of receiving points within the area receive a *C/N* of at least 10 dB. (See § 3.1 of Annex IV.)

Case D: As for Case C but with 95% of areas having 90% of points with a *C/N* value at least 10 dB. (See Annex II.)

Case E: This case applies to the advanced digital system for vehicular receivers operating in a slightly shadowed rural area. The channel is conservatively modelled as a Rayleigh fading channel with a mean excess path loss of 0 dB.

Case F: This case also applies to the advanced digital systems for vehicular receivers operating in a heavily shadowed rural area or even in a dense urban area where channel frequency selectivity must be taken into account. The channel is modelled as a Rayleigh fading channel with mean excess path loss of 10 dB.

For advanced digital systems, case F is directly comparable with Case B for analogue systems; the link margin is reduced by 5 dB because the advanced digital systems eliminate the effect of Rayleigh fading and thus only the factor (10 dB) representing the log-normal distribution of the field-strength over large aeras needs to be included (see Annex II).

Case G: This case applies to the operation of a portable receiver inside a single storey house. The channel is modelled as an additive white Gaussian noise (AWGN) channel with a mean excess path loss of 12 dB.

2.6.4 Link budgets for various systems

The link budgets for the various types of systems studied are given below.

2.6.4.1 FM systems

Table II shows the link budgets for the two FM system examples with the various link margin cases A, B, C and D as defined in section 2.6.3.3. The C/N values indicated are those required for an audio S/N of 40 dB (weighted, monophonic reception) and assume the use of a phase-locked-loop demodulator. (For a conventional demodulator a C/N value of about 10 dB would be necessary because of threshold effects). For a given standard of service the p.f.d required is less for companded FM with 10 kHz audio bandwidth than for conventional FM with 15 kHz bandwidth. For example, for link margin case "A", the p.f.d. values are -123.4 dB(W/m^2) and -114.1 dB(W/m^2), respectively.

TABLE II - Link budget at 1 GHz for FM systems

Polarization		Circular	
Type of modulation		FM companded	FM conventional
Reception mode		Monophonic	Monophonic(1)
Audio bandwidth	kHz	10	15
Carrier deviation	kHz	26.5	75
Noise bandwidth	kHz	73 (= 48.6 dBHz)	180 (= 52.6 dBHz)
Required (C/N) total(2)	dB	4.0	9.3
Subjective sound impairment grade	(3)	3	3
Degradation due to up-link C/N	dB	0.4	0.4
Required down-link C/N	dB	4.4	9.7
Implementation margin	dB	1	1
Receive antenna gain	dBi	5	5
Coupling loss	dB	1	1
Receiver noise temperature	K	600 (= 27.8 dBK)	600 (= 27.8 dBK)
Area of isotropic antenna at 1 GHz	dBm^2	-21.4	-21.4

Link margin case		A	B	C	D	A	B	C	D
Link margin	dB	6	15	25	33	6	15	25	33
Line-of-sight PFD at edge of beam (-3 dB)	$dB(W/m^2)$	-123.4	-114.4	-104.4	-96.4	-114.1	-105.1	-95.1	-87.1
Equivalent field strength at edge of beam (dB(μV/m))		22.4	31.4	41.4	49.4	31.7	40.7	50.7	58.7
Spreading loss	dBm^2	162.4	162.9	162.9	162.9	162.4	162.9	162.9	162.9
E.i.r.p. on axis	dBW	42	51.5	61.5	69.5	51.3	60.8	70.8	78.8
Transmitter power for 1° beamwidth	dBW	-1.9	7.6	17.6	25.6	7.4	16.9	26.9	34.9

(1) - Stereophonic reception is possible for fixed receiver with higher gain antenna.

(2) - The use of a phase-locked loop demodulator is assumed. This C/N is required for 40 dB audio S/N. It exceeds the PLL threshold.

(3) - See Recommendation 562.

2.6.4.2 FM system using space diversity on the vehicle

Table IV shows a link budget for a vehicular receiver using quad-spatial diversity and maximal ratio combining to receive an analogue FM channel [Miller, 1988]. The receiving environments correspond to those described as Case E (slightly shadowed rural area with Rayleigh fading and a mean excess path loss of 0 dB) and Case F (heavily shadowed rural area with Rayleigh fading and a mean excess path loss of 10 dB). It is noted that fixed and portable receivers do not require multiple antennas and signal combining circuitry in order to receive the analogue FM sound programme channel.

2.6.4.3 Simple digital systems

The example described in this section (see Table IV) is based on a source bit rate of 338 kbit/s per monophonic channel which can be obtained by near-instananeous companding [CCIR, 1982-86a] or by adaptive delta modulation.

A great number of modulation schemes exist. Most of those which can be detected with reasonably simple receiver circuitry have generally similar power requirements; they differ slightly in such areas as spectral characteristics, sensitivity to channel distortions (such as arise in the satellite high-power amplifier), and ease of demodulation. The example uses VSB 2-PSK.

The performance of these simple digital systems will be affected by the channel frequency selectivity. However, the link budget of this example refers to the best propagation case where no frequency selectivity occurs in the transmission channel.

2.6.4.4 *Advanced digital system I* (see also Annex III)

The advanced digital system example described in this section is based on a combination of technologies in various stages of development that should reach a suitable stage of development for satellite sound broadcasting for individual reception by portable and automobile receivers in or before 1990 [CCIR, 1986-90d]. The key features of this system are:

- the use of a low-cost adaptive delta modulation (ADM) sound encoding technique which has already been reduced to practice for high quality consumer audio applications [Dolby, 1985; Signetics, 1985];
- the use of convolutional coding (R = 1/2; K = 7) and Viterbi maximum likelihood decoding for forward error correction (FEC); and
- interleaving/de-interleaving as an effective means to mitigate the serious effects of rapid fading on the satellite-to-vehicular receiver propagation path;
- the use of spatial diversity reception on a vehicle to provide service continuity when the vehicle is stationary.

TABLE III

Link budget for an analogue FM satellite sound broadcasting system/s serving a vehicular receiver using quad-spatial diversity and maximal ratio combining

Polarization		Circular			
Type of modulation		FM companded		FM conventional	
Reception mode		Monophonic		Monophonic(1)	
Audio bandwidth	kHz	10		15	
Carrier deviation	kHz	26.5		75	
Noise bandwidth	kHz	73 (= 48.6 dBHz)		250 (= 54 dBHz)	
Required (C/N) total(2)	dB	4.0		10.0	
Subjective sound impairment grade (3)		3		3	
Degradation due to up-link C/N	dB	0.4		0.4	
Required down-link C/N	dB	4.4		10.4	
Implementation margin	dB	1		1	
Receive antenna gain	dBi	5		5	
Coupling loss	dB	1		1	
Receiver noise temperature	K	600 (= 27.8 dBK)		600 (= 27.8 dBK)	
Area of isotropic antenna at 1 GHz	dBm^2	-21.4		-21.4	
Link margin case		E	F	E	F
Link margin	dB	3.5	13.5	3.5	13.5
Line-of-sight PFD at edge of beam (-3 dB)	$dB(W/m^2)$	-125.9	-115.9	-114.5	-104.5
Equivalent field strength at edge of beam (dB(μV/m))		19.9	29.9	31.3	41.3
Spreading loss	dBm^2	163.0	163.0	163.0	163.0
E.i.r.p. on axis	dBW	40.1	50.1	51.5	61.5
Transmitter power for 1° beamwidth	dBW	0.4	4.2	5.8	57.5

(1) - Stereophonic reception is possible for fixed receiver with higher gain antenna.

(2) - The use of a phase-locked loop demodulator is assumed. This C/N is required for 40 dB audio S/N. It exceeds the PLL threshold.

(3) - See Recommendation 562.

TABLE IV - Link budget at 1 GHz for a simple digital system

Polarization	Circular
Type of modulation	VSB 2-PSK
Reception mode	Monophonic (1)
Error protection	Concealment
Total bit rate (kbit/s)	364
Required E_b/N_o (for 10^{-4} bit-error ratio) (dB)	8.4
Subjective sound impairment grade (2)	4
Required C/N_o total (dBHz)	64
Degradation due to up-link (dB)	0.4
Required down-link C/N_o (dBHz)	64.4
Implementation margin (dB)	1
Interference allowance (dB)	2
Receive antenna gain (dBi)	5
Coupling loss (dB)	1
Receiver noise temperature (K)	600 (= 27.8 dBK)
Area of isotropic antenna at 1 GHz (dB(m^2))	-21.4

Link margin case	A	B	C	D
Link margin (dB)	6	15	25	33
Line-of-sight PFD at edge of beam (-3 dB) (dB(W/m^2))	-110	-101	-91	-83
Equivalent field strength (dB(μ V/m))	35.8	44.8	54.8	62.8
Spreading loss (dB(m^2))	162.4	162.9	162.9	162.9
E.i.r.p. on axis (dBW)	55.4	64.9	74.9	82.9
Transmitter power for 1° beam (dBW)	11.5	21	31	39

(1) - Stereophonic mode requires doubling the total bit-rate. Consequently, the transmitter power would also be doubled.

(2) - See Recommendation 562

Link budgets for three link margin cases are given:

- a vehicular receiver operating in a heavily foliaged rural environment (10 dB excess path loss) (case F);
- a vehicular receiver operating in a lightly foliaged rural environment (0 dB excess path loss) (case E); and
- a portable receiver operating inside a house (12 dB excess path loss) (case G).

As discussed in section 2.6.3.3 and provided that the correlation bandwidth is small in comparison to the bandwidth of the transmitted signal, the first case is also comparable to a vehicular receiver operating in an urban environment with an excess path loss of 10 dB.

Values given in Table V for power flux-density and spectral power flux-density are some 10 to 20 dB less than for conventional FM or simple digital systems operating in a similar environment. **Note that comparable performance is available to the vehicular receiver solely by the use of quad-spatial diversity and maximal ratio combining. Relying on the use of space diversity in the vehicular receiver instead of time diversity permits the design and manufacture of fixed and portable receivers that are simpler and that should cost less.**

2.6.4.5 *Advanced digital system II (see also Annex IV)*

Advanced digital system II is specifically designed to overcome the frequency selectivity of the channel, so it is well suited for vehicular reception in urban environments [CCIR, 1986-90b, c]. It is based on:

- efficient source sound encoding with substantial bit-rate reduction;
- convolutional channel coding with Viterbi decoding;
- frequency and time interleaving in order to overcome selective fading effects;
- coded orthogonal frequency division multiplexing (COFDM);
- the use of a guard interval between two successive symbols.

Basic assumptions

- source bit rate per stereophonic sound programme: 168 kbit/s (system example A), 224 kbit/s (system example B);
- modulation: 4-PSK with differential detection;
- channel coding: frequency interleaving and convolutional code of rate 1/2 constraint length 7 and free distance 10;
- typical delay spread: 2 μs which is representative of dense urban environments in Europe.

Depending on the source rate (A or B) and with a total of 256 carriers, there are respectively 16 and 12 stereophonic programmes available in a 4 MHz band.

The link budget for Case F with a link margin of 10 dB is given in Table V.

TABLE V - *Link budget examples for an advanced digital satellite sound broadcasting system I operating in Band 9*

System parameter	Value
Type of modulation	QPSK
Reception mode	monophonic (1)
Bit rate (kbit/s)	204
Symbol rate (ksp/s)	408
Required RF bandwidth (kHz)	400
Received S/N (dB)	58
Subjective sound impairment grade (2)	4.5
Received bit-error ratio	10^{-5}
Audio bandwidth (kHz)	15
Carrier frequency (MHz)	1000

Link margin case	F		E	G
	Automobile			House
	Heavy foliage		Light foliage	
Receiver antenna gain (dBi)		5.0		5.0
Coupling loss (dB)		1.0		1.0
Receiver system noise temp. (K)		600		600
Required E_b/N_o (dB)		7.4		3.8
Implementation margin (dB)		1.0		1.0
Mean excess path loss (dB)	10		0	12.0
Line-of-sight PFD at beam edge (dB(W/m^2))	-111.8		-121.8	-113.4
Equivalent field strength at beam edge (dB(μV/m)	34.0		24.0	32.4
Maximum beam-centre PFD per 4 kHz (dB(W/(m^2·4 kHz)))	-125.9		-135.9	-127.5
Maximum spreading loss (φ_o = 17°) (dB/m^2)		163.0		163.0
E.i.r.p. on-axis (dB(W))	54.2		44.2	52.6
Satellite antenna gain (D=20 m) for 1° beamwidth (dBi)		43.9		43.9
Antenna input power (dB(W))	10.3		0.3	8.7
Antenna input power (W)	10.7		1.1	7.4

(1) - Stereophonic mode requires doubling the bit rate. Consequently the symbol rate, required RF bandwidth and antenna input power would also be doubled.

(2) - See Recommendation 562

TABLE VI

Link budget for the advanced digital system II (1 GHz)

	System example A (16 progr./4 MHz)	System example B (12 progr./4 MHz)
Polarization	Circular	Circular
Error protection	FEC (1/2)	FEC (1/2)
Total bit rate per stereophonic sound programme (kbit/s)	336	448
Required E_b/N_o for 10^{-3} BER (dB)	8.5	8.5
Subjective sound impairment (1)	4.5	4.5
Required C/N_o total per stereophonic channel (dBHz)*	60.8	62
Degradation due to up-link C/N_o (dBHz)*	0.4	0.4
Required down link C/N_o (dBHz)*	61.2	62.4
Implementation margin (dB)**	2	2
Interference allowance (dB)	1	1
Receive antenna gain (dBi)	5	5
Coupling loss (dB)	1	1
Receiver noise temperature (K)	600 (=27.8 dB/K)	600 (=27.8 dB/K)
Satellite antenna gain for 1° beamwidth (dBi)	43.9	43.9
Standard of service (see § 6.4.2)	F	F
Link margin (dB)	10	10
Line-of-sight PFD at beam edge (-3 dB) (dB<W/m^2>)*	-109.2	-108
Equivalent field strength at beam edge (dBμV/m)*	36.6	37.8
Line-of-sight PFD at beam centre per 4 kHz for the full sound multiplex (dBW/<m^2 4 kHz>)	-123.6	-123.6
Spreading loss (dB/m^2) (δ = 17°)	163	163
E.i.r.p. on axis (dBW)*	56.8	58
Antenna input power for a 1° beam (dBW)* (2)	12.9	14.1
Antenna input power for a 1° beam (W)*	19.5	25.7

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* These figures describe the power, etc. requirements per stereophonic programme.

** This value includes a 1 dB allowance for the use of a 20% guard interval (see Annex IV).

(1) See Recommendation 562

(2) These link budgets have been calculated on the basis of input power to the antenna to satisfy given link quality criteria. Given the distortion that will arise for the complex modulation system used, it is probable that the final output amplifier will have to operate under backoff. Whilst future studies continue, it is currently expected that the necessary output backoff value will be between 4 and 5 dB.

2.7 *Sharing* considerations

The frequency band selected for the sound broadcasting satellite service will affect inter-service sharing. The sharing possibilities are dependent upon the permissible level of interference into existing services and susceptibility of the newly proposed service to interference from the existing services. Assuming a fixed receiving antenna gain for near omni-directional reception, the required level of p.f.d. for acceptable reception quality will increase with an increase in frequency and conversely will decrease with a decrease in frequency.

The Table of Frequency allocations for bands within, and also outside but near the range 500 MHz - 2 000 MHz provides for numerous radiocommunication services, including broadcasting, fixed and mobile services, as well as aeronautical, radionavigation and radiolocation services. Sharing criteria were, however, found to be only available at this time for the broadcasting, fixed and mobile services in certain bands.

2.7.1 *Application of system models to sharing*

Section 2.6 describes several systems which represent a wide range of possible cases which can be applied to different receiving situations in rural and urban areas and at high or low latitudes. From these, four system models have been selected which are believed to represent the most likely applications. Table VII contains the parameters of these four system models which are relevant to sharing considerations. Table VII is based on operation at 1 GHz for all systems.

TABLE VII - *System model parameters relevant to sharing*

System	Conventional FM	Companded FM	Digital	Advanced Digital(1)
Class of service	A(2)	A(2)	A(2)	F(3)
Link margin	6 dB	6 dB	6 dB	10 dB(4)
PFD at the centre of the coverage area(5) (dBW/m^2)	-111.1	-120.4	-107	-109
PFD/4 kHz at the centre of the coverage area(5) ($dB(W/(m^2 \cdot 4kHz))$)	-111.1(6)	-120.4(6)	-123.6	-126

(1) Two different advanced digital systems with almost equal sharing parameters are represented in this column

(2) Intended for reception in rural areas at low latitude

(3) Intended for reception in dense urban areas at high latitude

(4) Equivalent to 15 dB for the other systems

(5) The PFD increases with the square of the operating frequency. (3.5 dB higher value required at 1.5 GHz; 6 dB lower value at 500 MHz)

(6) No energy dispersal was assumed in these cases.

2.7.2 *Energy dispersal*

Energy dispersal may be desirable to facilitate sharing between the broadcasting-satellite service (sound) and the terrestrial services. There are two forms of energy dispersal. The first is natural energy dispersal associated with the characteristics of the information (sound programme) and the modulation method; and the second is artificial energy dispersal applied to the transmitted signal to spread the power flux density over a larger bandwidth and thus decrease the spectral power flux density.

Natural energy dispersal associated with the analogue FM transmission method for satellite sound broadcasting is virtually nil because of the pauses in speech and programme transition times. During these pauses, the carrier is radiated at full power at its rest frequency. Natural energy dispersal associated with transmitter oscillator instability is expected to be negligible for satellite sound broadcasting systems operating in Band 9. Artificial energy dispersal may however be used with analogue FM transmission systems for improved sharing with narrow-band services. The method described in Report 384-4 for use in multi-channel FDM/FM telephony transmission systems can be applied to satellite sound broadcasting systems.

Natural energy dispersal associated with digital satellite sound broadcasting systems can be substantial. The advanced systems specified in this chapter can provide energy dispersal gain in the range from 17 to 19 dB in a reference bandwidth of 4 kHz compared to an unmodulated carrier. The realization of this degree of energy dispersal requires that the modulating digital sequence approaches a truly random sequence of 1's and 0's. Details about the corresponding procedure can be found in Annex III to Report 384-4.

In order to achieve a similar energy dispersal gain with the FM system (17 dB), a peak-to-peak deviation of 200 kHz would be required. However, the use of such artificial energy dispersal could require modifications of conventional receivers.

2.7.3 Overview of sharing situations

To provide a comprehensive picture of sharing situations, the services which have an allocation in the UHF bands are considered in Table VI. The table lists the services, by frequency band, and indicates the corresponding constraints which are either laid down in the Radio Regulations or studied in CCIR texts, with cross references to the more specific sharing criteria contained in Table VII. These tables are provided as a means to understand the overall sharing situation in the frequency range 0.5 - 3 GHz as it may relate to BSS (sound) and they may not contain all the sharing aspects indicated in Article 8 of the Radio Regulations.

2.7.4 *Analysis of specific sharing situations*

2.7.4.1 *Sharing with the terrestrial television broadcasting service*

To protect the terrestrial broadcasting service operating in the UHF band from interference caused by a sound broadcasting satellite service, it is essential to determine the permissible power flux-density generated by the satellite in the service area of the terrestrial television broadcasting station. Sharing will be facilitated with systems producing the lowest power flux-density, whether energy dispersal is used or not.

TABLE VIII
(Source: Table 6-X in the CCIR Report to WARC ORB-88)

pfd limits by frequency bands

(For full information on sharing conditions see Article 8 of Radio Regulations)

Band (MHz)	Interfered services with specified limits*	Notes	Strictest limit (for elevation angle = 0)	Cases referred to Table VII
470 - 890	Broadcasting Radioastronomy (608-614)	(4)	-129 dB(W/m²) -136 dB(W/m²) -185 dB(W/m²) in 6 MHz	A RR: Rec. 705 G CCIR Rep. 631 I CCIR Rep. 224
890 - 960	Fixed Mobile		-146 dB(W/(m²·16 kHz))	H CCIR Rep. 631
960 - 1 215		(3)		
1 215 - 1 240		(3)		
1 240 - 1 300		(3)		
1 300 - 1 350		(3)		
1 350 - 1 400		(3)		
1 400 - 1 427	Radioastronomy	(4) (1)	-180 dB(W/m²) in 27 MHz - 80 dB(W/m²) typically	I CCIR Rep. 224 J CCIR Rep. 697
1 427 - 1 525		(3) (7)		
1 525 - 1 530	Fixed Mobile	(5)	-154 dB(W/m²) in 4 kHz	C RR: Article 28 Section IV
1 530 - 1 535		(8) (5)		
1 535 - 1 626.5		(3)		
1 626.5 - 1 660.5	Radioastronomy (1 660.5 - 1 660.5)	(4)	-194 dB(W/m²) in 20 kHz	I CCIR Rep. 224

* According to current Radio Regulations and CCIR Reports or Recommendations

TABLE VIII(continued)
(Source: Table 6-X (continued) in the CCIR Report to WARC ORB-88, except the last two rows)

Band (MHz)	Interfered services with specified limits*	Notes	Strictest limit (for elevation angle = 0)	Cases referred to Table VII
1 660.5 - 1 670	Radioastronomy	(4) (1)	-194 dB(W/m²) in 20 kHz - 80 dB(W/m²) typically	I CCIR Rep. 224 J CCIR Rep. 697
1 670 - 1 700	Meteorological aids	(5)	-133 dB(W/m²) in 1.5 MHz	B RR: Article 28 Section IV
1 700 - 1 710	Fixed Mobile	(5)	-154 dB(W/m²) in 4 kHz	C RR: Article 28 Section IV
1 710 - 2 290		(3)		
2 290 - 2 300	Fixed Mobile	(5)	-154 dB(W/m²) in 4 kHz	C RR: Article 28 Section IV
2 300 - 2 483.5		(3)		
2 483.5 - 2 500	Fixed Mobile	(6)	-154 dB(W/m²) in 4 kHz	C RR. Article 28 MOD 2558, 2559
2 500 - 2 655	Fixed Mobile	(2)	-152 dB(W/m²) in 4 kHz	E RR: Article 28 Section IV
2 655 - 2 690	Fixed Mobile	(2)	-152 dB(W/m²) in 4 kHz	E RR: Article 28 Section IV
2 690 - 2 700	Radioastronomy	(4) (1)	-177 dB(W/m2) in 10 MHz -76 dB(W/m2) typical value	I CCIR Rep. 224 J CCIR Rep. 697
2 700 - 3 100		(3)		

* According to current Radio Regulations and CCIR Reports or Recommendations.

Notes to Table VIII
(Source: Table 6-X in the CCIR Report to WARC ORB-88)

(1) This limit applies to services whose intermodulation products can arise in a band where the radioastronomy service has an allocation.

(2) The BSS in the band 2 500 - 2 690 MHz is limited to national and regional systems for community reception (see No. 761 of the Radio Regulations). Furthermore, in some countries this is an alternative allocation and the BSS consequently has no allocation in this band. Services in the band 2 655 - 2 690 MHz are obliged to take all practicable steps to protect the radioastronomy service in the band 2 690 - 2 700 MHz.

(3) No limit specified.

(4) Table I or Table II of CCIR Report 224. To enable radioastronomy observations to be carried out at 5° from the geostationary orbit, levels 15 dB lower are required (see § 4.3 of CCIR Report 224 and CCIR Recommendation 611); e.g. for the band 470 - 890 MHz the level would be -200 dB(W/m^2).

(5) In the case of tropospheric scatter systems, refer to Article 28, in particular No. 2560, of the Radio Regulations.

(6) This limit was adopted by WARC MOB-87 in the band 2 483.5 - 2 500 MHz (see Radio Regulations, Article 28, MOD 2558, 2559).

(7) CCIR Report 941 considers sharing between the broadcasting-satellite service (sound) and the fixed service in this band. CCIR Report 955-1 considers sharing between these two services in the band 0.5 - 2 GHz.

(8) The limits of RR Article 28, Section IV, apply up to 1 January 1990.

In Report 631-3, the EBU has suggested a minimum field strength of 65 dB (μV/m), and the USA suggested 56 dB (μV/m). Furthermore, the EBU considered that a corresponding protection ratio of 54 dB be employed and the USA suggested 35 dB to protect terrestrial TV broadcasting from the BSS (TV-FM). (Indications are however that the 54 dB protection ratio could be pessimistic in the case of digitally modulated carriers.)

This results in a range of permissible power flux-density for the satellite sound broadcasting service ranging from -132 dB(W/m^2) to -122 dB(W/m^2) (aggregate per television channel) based on the range of minimum field-strength values to be protected as seen above and assuming a 3 dB reduction in interference from the use of circular polarization.

65 dB (μV/m) - 146 dB(W/uVm) - 54 dB + 3 dB = -132 dB(W/m^2)
56 dB (μV/m) - 146 dB(W/uVm) - 35 dB + 3 dB = -122 dB(W/m^2)

Furthermore, No. 693 of the Radio Regulations provide a PFD of -129 dB(W/m^2) for use by the BSS (TV-FM) in the band 620-790 MHz.

TABLE IX
(Source: Table 6-XI in the CCIR Report to WARC ORB-88)

Specific sharing criteria

	References	Interfering services	Services subject to interference	Bands (MHz)	PFD limits (δ = elevation angle)
A	RR: Rec. 705	Broadcasting satellite	Terrestrial broadcasting	620-790	-129 for $0° \le \delta < 20°$ -129+0.4 (δ - 20) for $20° \le \delta < 60°$ -113 for $60° \le \delta < 90°$ dB(W/m²) on a provisional basis
B	RR: Article 28 Section IV	Earth exploration satellite Meteorological satellite	Meteorological aids	1 670-1 700	-133 dB(W/m²) in any 1.5 MHz band
C	RR: Article 28 Section IV	Meteorological satellite	Fixed	1 525-1 530 for Regions 1 and 3	-154 for $0° \le \delta < 5°$
		Space research	Mobile	1 530-1 535 for Regions 1 and 3	-154+0.5 (δ -5) for $5° \le \delta < 25°$
		Space operation		1 670-1 690 1 690-1 700 1 700-1 710 2 290-2 300	-144 for $25° \le \delta < 90°$ dB(W/m²) in any 4 kHz band
		Radiodetermination-satellite		2 483.5-2 500	-154 dB(W/m²) in 4 kHz
D	RR: Article 28 Section IV 2560	The same as in case C	Fixed using tropospheric scatter	The same as in case C	-168 dB(W/m²) in any 4 kHz band at the receiver input of the station of the fixed service
E	RR: Article 28 Section IV	Broadcasting satellite Fixed satellite	Fixed Mobile	2 500-2 690	-152 for $0° \le \delta < 5°$ -152+0.75 (δ- 5) for $5° \le \delta < 25°$ -137 for $25° \le \delta < 90°$ dB(W/m²) in any 4 kHz band
F	CCIR: Rec. 358-3	Fixed satellite	Fixed (line-of-sight) Mobile (line-of-sight)	2 500-2 690	-152 for $0° \le \delta < 5°$ -152+0.75 (δ- 5) for $5° \le \delta < 25°$ -137 for $25° \le \delta < 90°$ dB(W/m²) in any 4 kHz band
G	CCIR Report 631-3	Broadcasting-satellite	Terrestrial broadcasting	620-790	Proposals for the provisional limits given in RR Rec.705 (case A) -129 becomes -136 (EBU) -125 (USA) -124 (USSR)
H	CCIR Report 631-3	Broadcasting-satellite	Mobile service (under some hypotheses)	around 800	High quality: -133 dB(W/(m² · 16 kHz)); mobile station -146 dB(W/(m² · 16 kHz)); base station Medium quality: -127 dB(W/(m² · 40 kHz)); mobile station -134 dB(W/(m² · 40 kHz)); base station
I	CCIR Report 224-6		Radioastronomy	408 610 1 420 1 420 1 665	For continuum: -189 dB(W/m²) in 3.9 MHz -185 dB(W/m²) in 6.0 MHz -180 dB(W/m²) in 27 MHz For spectrum lines: -196 dB(W/m²) in 20 kHz -194 dB(W/m²) in 20 kHz
J	CCIR Report 697-2	Intermodulation of out-of-band signals	Radioastronomy	1 400-1 427 1 660-1 670	-80 dB(W/m²) (1)

(1) This limit applies to services whose intermodulation products can arise in a band where radioastronomy service has an allocation."

Assuming an operational condition whereby each service area would be covered by 4 sound channels, all within the same television channel, and a receiving location at the edge of two adjacent service areas (where the signal is reduced by 3 dB), where reception from two satellite systems would be possible, the aggregate effect would correspond to a 6 dB increase in received unwanted PFD.

Considering the required p.f.d. for the system models mentioned in § 2.7.1 and comparing it to the permissible p.f.d. limits set above for single entry and aggregate cases, values for the required additional isolation for the non-constrained operation of the two services can be found. These values are given in Table X for the four system models. Such additional isolation can only be provided through both the discrimination from the satellite transmitting antenna on the basis of geographical sharing, as will be covered in § 2.7.5, and through the discrimination of the television receiving antenna towards the satellite.

In the case of the discrimination from the television receiving antenna towards the satellite, the elevation angle dependency, as implied in RR Rec. 705, will be assumed in this Report. We note, however, that in RR 693, no restriction is given above 20°.

$$\begin{array}{lll} \text{PFD (dB(W/m}^2)) & & \text{for } \delta \leq 20^\circ \\ \text{PFD} + 0.4\ (\delta - 20) & (\text{dB(W/m}^2)) & \text{for } 20^\circ < \delta \leq 60^\circ \\ \text{PFD} + 16\ (\text{dB(W/m}^2)) & & \text{for } 60^\circ < \delta \leq 90^\circ \end{array}$$

TABLE X - *Additional isolation required to allow sharing between the sound BSS and the* terrestrial broadcasting service

System	PFD at centre of coverage area (dB(W/m^2))	Required isolation (minimum/maximum) (dB)
Conventional FM	-111.1	16.9/26.9
Companded FM	-120.4	7.6/17.6
Digital	-107	21/31
Advanced digital	-109	19/29

Receiving installations located at low latitudes can be able to take fullest advantage of this discrimination from the receiving antenna. Some advantage can be available at higher latitudes.

Upon more detailed consideration of the protection ratios for narrow-band carriers interfering into the television broadcasting service, it can be found that Recommendation 418 and Report 306 indicate some relaxations in protection ratios for certain relationships between the wanted and interfering television channel signal spectra. A 10 dB relaxation in protection ratio is feasible if the nominal frequency difference between the wanted television carrier and the unwanted sound carrier is an odd multiple of half the line frequency and the interfering carrier is not in the region of the colour sub-carrier. Furthermore, in the region between the low frequency luminance spectrum and the chrominance spectrum located around the colour sub-carrier, the television signal is less susceptible to interference from narrow-band carriers. A maximum relaxation of 10 dB to 20 dB, depending on the television system, is feasible in this region with 15 dB as a common value which would be applicable throughout. It should be noted, however, that only a limited number of carriers can be fitted in this less critical region of the television signal. Finally, in the region adjacent to the sound carrier, indications are that a relaxation of 25 dB in the protection ratio would be feasible over a relatively narrow band.

In those cases where the width of the frequency slot only allows for a limited number of sound carriers, the 6 dB aggregate value used in Table X can be decreased accordingly.

In the specific case where a single sound BSS carrier is located close to the television sound carrier, a total relaxation of 31 dB from the protection values used in Table X can be assumed.

It should be realized, however, that the relaxations as described above based on specific interfering sound carrier locations within the television channel, will only be feasible on a common basis if the television channels have been assigned according to a regular channel plan, i.e., as is the case in Region 2 (universal 6 MHz channel separation).

For all the cases mentioned below where geographical separation is required to avoid interference into the television broadcasting service, there is no need to consider the interference aspects in the reverse direction, namely from the television signal into the satellite sound broadcasting receiver since the geographical separation to insure a proper discrimination from the satellite transmitting antenna would bring the service area of the satellite sound broadcasting clearly beyond the coverage of the television transmitter.

However, in those cases where co-located operation is possible without undue interference to television broadcasting, further consideration should be given to the possibility that the television signal will create an unacceptable level of interference to the reception of the sound BSS.

Table X shows the required isolation to permit sharing with the terrestrial broadcasting service.

Sharing with conventional FM will be more difficult than in the case of companded FM. It should be noted that for both FM cases, the sharing situation would have been more difficult if it had been applied to the urban case. With respect to the digital systems, the greatly improved performance of the advanced system is accompanied by slightly improved sharing possibilities. Consideration of the discrimination available from the television receiving antenna improves the situation. Geographical sharing will be greatly facilitated for those areas between the sub-satellite point and the coverage area. For sharing with areas at an elevation angle of 60° to the satellite, 16 dB additional isolation would be afforded.

2.7.4.2 *Sharing with fixed services*

Since most systems in the fixed services are of the narrow band type, the sharing criteria are based on the spectral power flux-density (per 4 kHz). Consequently, energy dispersal will greatly improve the sharing situations. In the case where no energy dispersal can be applied to preserve compatibility with present FM receivers, the sharing will be quite difficult. This is supported by a study on sharing with fixed services in the 1429 MHz to 1525 MHz band as given in Report 941. This Report, based on the assumption of conventional FM transmission, is rather pessimistic on the acceptability of sound BSS in the 1500 MHz band.

The following permissible power flux-density limits for sharing with the fixed services at 1.7 GHz are taken from RR 2557. Assumption will be made that these limits can be used in order to provide a p.f.d. limit for this discussion, for all frequency bands where sharing between FS and sound BSS is considered. Furthermore, these limits are used in the present context as threshold p.f.d. values above which the interference to the fixed services would be considered unacceptable:

-154 dB(W/(m^2 · 4 kHz))	for $\delta \leq 5°$
$-154 + (\delta - 5)/2$ dB(W/(m^2 · 4 kHz))	for $5° < \delta \leq 25°$
-144 dB(W/(m^2 · 4 kHz))	for $25° < \delta \leq 90°$

It can be noticed that, in the 2.6 GHz band, the permissible p.f.d. for community reception, as per Radio Regulations 2562 to 2564, gives values very close to those stated above. Table XI shows the required isolation to permit sharing with the fixed service.

TABLE XI - *Required additional isolation to allow sharing between the sound BSS and the fixed service*

Systems	PFD at centre of coverage area (dB(W/(m^2 · 4kHz))	Required isolation (dB)	
		Low elevation angle	High elevation angle
Conventional FM	111.1	42.9	32.9
Companded FM	-120.4	33.6	23.6
Digital	-123.6	30.4	20.4
Advanced digital	-126	28	18

It can be seen from this Table that additional discrimination is required in all cases to allow sharing.

2.7.4.3 *Sharing with the mobile service*

The permissible power flux-density values are given in CCIR Reports 770, 631 and 358 for land mobile systems operating at frequencies between 470 MHz and 960 MHz and more specifically between 806 MHz and 942 MHz in Region 2. Report 770 provides directly applicable typical data whereas other sources, in particular Report 358, give the background considerations. These values are summarized in Table XII below for low elevation angles (below 20°) to provide protection to high grade services.

As seen in Table XII, the worst case of p.f.d. not to be exceeded is given in Report 770.

These limits have been used in the preparation of Table XIII. The required isolation referred to in Table XIII refers to p.f.d. limits for a base station. This will be the worst case unless the receiving antenna discrimination for a signal arriving from sound BSS exceeds 16 dB. Beyond this value, the mobile station will become the constraining case.

TABLE XII - *Typical system parameters and permissible p.f.d. for mobile services*

CCIR Reports	Base station			Mobile station		
	PFD (dB(W/m^2))	Band-width (kHz)	Receiving antenna gain (dB)	PFD (dB(W/m^2))	Band-width (kHz)	Receiving antenna gain (dB)
631	-146	16	15	-133	16	
358	-142.1	16		-132.1	16	
770	-147.9	30	17	-132	30	4.1

TABLE XIII - *Additional isolation required to allow sharing between the sound BSS and mobile services*

Systems	PFD at centre of coverage area (dB(W/(m^2 · 4 kHz)))	Required isolation (Report 770) (dB)
Conventional FM	-111.1	36.8
Companded FM	-120.4	27.5
Digital	-123.6	33
Advanced digital	-126	30.6

As can be seen from this Table, additional isolation will be required in all cases to permit sharing with the mobile service.

2.7.5 *Geographical sharing*

Geographical sharing can be used to resolve some difficult sharing situations. In such cases, co-located sharing of a given frequency band between the two concerned services is *not* possible: in contrast, for sharing to take place between networks of the two services in question, a *geographical separation* of the service areas of the two networks is required. When both of the services in question are terrestrial in nature, the geographical separations required may be in the tens to hundreds of kilometres in the UHF portion of the radio spectrum. In contrast, when one of the services is a space service, in this case the sound broadcasting satellite service, the separation required may be in hundreds to thousands of kilometres.

The concept of geographical sharing between the sound broadcasting satellite service and a terrestrial service is dependent on the permissible flux level from the sound broadcasting satellite space station into the terrestrial network. The actual level is determined by the power flux-density needed in the service area of the sound broadcasting satellite service and the required level of protection to the terrestrial service. The difference between these two levels will determine the amount of isolation between the two services to operate without undue interference to the terrestrial service. This isolation can be provided by the discrimination of the satellite transmitting antenna if the service area of the terrestrial service is located far enough from the satellite beam coverage. In situations where required separation distances are small, interference from the terrestrial network into sound BSS receivers should also be considered.

Section 2.4 of this Report deals with satellite transmitting antenna technologies and indicates that good sidelobe rejection will be possible in the future and that the reference pattern used at the WARC-77 to plan the BSS at 12 GHz could be realistically assumed.

Table XIV gives the separation distances needed for different required antenna discriminations for the minimum case where the satellite beam covers an area close to the satellite sub-point; and for the maximum cases where the beam is directed away from the satellite sub-point and the location where the interference occurs is just at the edge of the Earth where the interfering signal from the satellite arrives at 0° elevation angle. These separation distances indicate the radius around the centre of the beam beyond which there is enough discrimination from the satellite antenna alone to allow frequency re-use by other services.

TABLE XIV - *Range of required separation distances on the Earth from the sound BSS beam centre to ensure a given satellite antenna discrimination for 1° and 2° antenna beamwidths*

Required antenna dicrimi-nation (dB)	Separation distance (km)				
	Off-axis angle (x φ_o)	$\varphi_o = 1°$		$\varphi_o = 2°$	
		Minimum	Maximum	Minimum	Maximum
3	0.5	312	2108	624	2965
10	0.91	570	2835	1142	3990
20	1.29	807	3362	1620	4742
30	1.58	989	3716	1988	5251
30.1	3.19	2007	5275	4098	7578
35	5.01	3183	6655	6740	9876
40	7.94	5183	8573	12938	14464

From the distances found above, geographical sharing can be applied to all cases of sharing where additional isolation beyond what is available from the receiving antenna is found to be necessary in order to allow operation of the sound BSS without affecting terrestrial services. This results in given separation distances for each specific case of sharing. These sharing situations along with their separation distances are summarized in Table XV.

TABLE XV - *Summary table of the situations and required separation distances*

Sound BSS system model	Interfered with service	Permissible PFD for sound BSS	Required isolation (dB)	Minimum separation distance for 1° beam (km) Elevation Angle (degrees)		
				5	30	60
Conventional FM (Case A)	Broadcasting					
	- maximum protection	-138 dB(W/m²)	10.9-26.9	3104	1510	676
	- minimum protection	-128 dB(W/m²)	0.9-16.9	2717	1181	199
(-111.1 dB (W/m²)) (-111.1 dB(W/(m²·4 kHz)))	Fixed	-154 dB(W/(m²·4 kHz))	32.9-42.9	9570	3652	2728
	Mobile - low elevation angle	-147.9 dB(W/(m²·30 kHz))	36.0	6741	4827	--
Companded FM (Case A)	Broadcasting					
	- maximum protection	-138 dB(W/m²)	1.6-17.6	2749	1208	264
	- minimum protection	-128 dB(W/m²)	0 - 7.6	2151	668	0
(-120.4 dB(W/(m²)) (-120.4 dB(W/(m²·4 kHz)))	Fixed	-154 dB(W/(m²·4 kHz))	23.6-33.6	5693	1529	981
	Mobile - low elevation angle	-147.9 dB(W/(m²·30 kHz))	27.5	3124	1631	--
Digital (Case A)	Broadcasting					
	- maximum protection	-138 dB(W/m²)	15-31.0	4976	1618	789
	- minimum protection	-128 dB(W/m²)	5-21.0	2892	1330	463
(-107 dB(W/m²)) (-123.6 dB(W/(m²·4 kHz)))	Fixed	-154 dB(W/(m²·4 kHz))	20.4-30.4	4824	1437	915
	Mobile - low elevation angle	-156.7 dB(W/(m²·4 kHz))	33.1	5547	3704	--
Advanced digital (Case F)	Broadcasting					
	- maximum protection	-138 dB(W/m²)	13-29.0	3171	1567	736
	- minimum protection	-128 dB(W/m²)	3-19.0	2810	1260	361
(-109 dB(W/m²)) (-126 dB(W/(m²·4 kHz)))	Fixed	-154 dB(W/(m²·4 kHz))	18.0-28.0	3140	1363	861
	Mobile - low elevation angle	-156.7 dB(W/(m²·4 kHz))	30.7	4899	3118	--

Case "A": Sound BSS intended for reception in rural areas at elevation angles exceeding 70°, corresponding to a service in low-latitude areas.

Case "F": For vehicular reception in heavily shadowed rural areas or in dense urban areas.

2.7.6 *Sharing with other services*

Besides the primary users of the 500 MHz to 2000 MHz band and its neighbourhood (broadcasting, mobile and fixed services), substantial allocations are provided for aeronautical, radionavigation and radiolocation services. Special sharing constraints on the use of adjacent bands may also arise from passive services such as radioastronomy services. Data for sharing with these other services are not yet available.

2.7.7 *Susceptibility of the sound BSS to interference from other services*

The susceptibility of the different analogue and digital modulation schemes to the interference from the other services with which the same frequency band is to be shared should be considered so that a complete picture of the sharing situation, in both directions, can be established for those cases where geographical separation is not required. It is expected that the digital systems, and even more so the advanced digital systems, will be more robust against interference than their analogue counterparts.

2.7.8 *Discussion of sharing situations*

It should be noted from the outset that the four system models used in the sharing analysis are typical system examples with specific system parameters and operating under given receiving conditions. In this way, the findings as to their sharing feasibility are not absolute since variations in the system parameters and operating conditions will ease or worsen the sharing conditions. For instance, the first three system models selected are assumed to be for reception in rural areas at low latitude. If reception in urban environments was to be covered, the necessary PFD level would need to be increased by 9 dB, therefore making the sharing more difficult. On the other hand, in the case of the fourth system (advanced digital), the grade of service was selected to cover reception in urban areas at high latitude with such systems. Operation in rural areas and low latitudes would make sharing conditions easier. In this study, the p.f.d.s have not been adjusted for operating frequencies different from the 1 GHz assumed. Operation at lower frequency would result in reduction of system PFD, for instance 6 dB at 500 MHz. In the case of sharing with the broadcasting service, some p.f.d. reduction would always be applied since the allocation is below 890 MHz. Also the chart shows a range of distances required for sharing with broadcasting services for various elevation angles. The three elevation angles shown, 5, 30 and 60 degrees, cover the range of discrimination in the vertical plane of the UHF TV receiving antenna assumed in this report, that is, from zero to 16 dB as the elevation angle of the sound BSS signal is increased above the horizontal plane.

It should be noted that the satellite transmitting reference pattern has a plateau at 30 dB isolation which represents a transition of about 1000 km. For those required isolation values slightly exceeding 30 dB, all means should be taken to reduce the isolation to less than 30 dB to obtain a substantial improvement in the sharing situation.

For the conventional FM system, the required separation distances found in Table XV indicate that sharing with fixed and mobile services would not be feasible. For the sound BSS to share with terrestrial broadcasting, a 199 to 3,104 km distance is required (which could further be reduced in the case of operation at lower frequencies) making near co-location possible in some situations at lower latitudes. Near co-location corresponds to the case where the TV station is outside but near the satellite coverage area, a situation which bears similarity to the existing inter-service sharing environment for terrestrial television.

In the case of the companded FM system, the sharing with the terrestrial broadcasting service requires even smaller separation distances (0 to 2,749 km) than for the case of conventional FM discussed above. Therefore, in some cases, operation in the same geographic area would be possible at the lower latitudes, considering only interference from BSS sound broadcasting space station transmitters to terrestrial UHF receivers. However, interference in the reverse direction, that is from terrestrial UHF TV transmitters, which have powers up to 5 megawatts, could cause interference to BSS earth station receivers in large areas around TV stations.

Sharing with the fixed service for low elevation angles requires large distances which can be diminished if energy dispersal is employed. In the case of areas with high elevation angles, sharing with the fixed service would permit near co-located operation with energy dispersal (an energy dispersal removal circuit can be assumed since new receivers with expanders would need to be manufactured in any case). Sharing with the mobile service will require relatively large separation distances which could be diminished to approximately 500 km with energy dispersal.

Considering the simple digital system, a range of 463 to 4976 km is required for sharing with the broadcasting service. Since the p.f.d. for all the operating frequencies must be adjusted, the threshold of 30 dB could easily be avoided and much smaller distances would be needed. Sharing with the fixed service will only be possible in the case of low elevation angles below 1 GHz at very large distances. At high elevation angles, sharing at a lesser distance will be possible. Sharing with mobile services will only be possible below 700 MHz and even so requiring large separations.

The advanced digital system, in order to share with the broadcasting service, requires distances ranging from 361 to 3171 km. This means that co-location would be possible at high elevation angles. Furthermore, at a frequency of 500 MHz, near co-location would be possible, for elevation angles above 45°. Sharing is feasible with the fixed service at medium to large distances depending on operating frequencies. Regarding sharing with the mobile service, it is only feasible below 1 GHz and then only for large separation distances.

2.8 *Bandwidth considerations* [CCIR, 1978-82a] [CCIR, 1986-90a, b]

The total bandwidth required for a band 9 sound BSS depends on the modulation method and the extent of coverage overlap.

For conventional FM and based on the parameters with appropriate modification used for the planning of the broadcasting-satellite service in the 12 GHz band in Region 1, one can conclude from a study carried out by the EBU and ESA covering almost the whole of Africa and Europe that approximately 60 channels with a spacing of 150 kHz and thus, a total bandwidth of about 9 MHz is necessary to provide one national sound broadcasting programme per country. This study is valid for monophonic as well as sterephonic reception. The latter will, however, only be achievable with permanently-installed receivers. The higher protection ratio needed for the higher quality stereophonic FM reception is obtained through:

- the line-of-sight reception of permanently-installed receivers requiring no fade margin; and
- the radiation characteristics of the high-gain receiver antenna which makes it possible to discriminate between the wanted and interfering satellites if the latter are in different orbit positions.

A study conducted in Canada for Region 2 based on the RARC SAT-83 service areas concludes that frequency re-use will not be possible and consequently 10.8 MHz are needed for one national programme per service area. A different coverage approach with a higher degree of overlap results in a bandwidth increase.

Simple digital modulation methods tend to require larger transmission bandwidths per channel which, however, is partly balanced by the lower sensitivity to interference. A study made for Region 2 countries indicates a bandwidth requirement of some 13 MHz for one monophonic programme per Region 2 country. Stereophonic transmissions would consequently require 26 MHz.

The frequency of the carrier within the 500-2000 MHz band affects the level of frequency re-use and hence affects the amount of spectrum required to provide one programme per service area. A lowering of the operating frequency will increase the size of the minimum beam for a given minimum antenna size. The angular distance before the frequency can be re-used will consequently increase thus increasing the spectrum requirement until a point where frequency re-use becomes impossible. From that point onward, the spectrum requirement stays constant. In a study for Region 2, it was found that the spectrum requirement decreased by 25% going from 1 GHz to 2 GHz whereas a smaller increase, between 0% and 12%, was found going from 1000 MHz to 500 MHz.

Advanced digital system II uses, as a matter of principle, channels which are 4 MHz wide in which 12 to 16 stereophonic programmes are transmitted. A planning exercise has shown that with this system a total band of 84 MHz (i.e. 21 channels) can provide one 4 MHz channel with national coverage for each European country. This total bandwith may be reduced if the service areas are identical and regularly distributed.

2.9 *Feeder-link considerations* [CCIR, 1978-82a]

Feeder links for satellite sound broadcasting systems will likely be accommodated in bands allocated to the fixed satellite service. The required bandwidth will likely be small in terms of present FSS usage and will be commensurate with the bandwidth allocated to the broadcasting-satellite service (sound) down links.

2.10 Cost considerations

The economics of introducing a new broadcasting service depend on many factors, including the context in which it is to be introduced [Stott, 1985].

It is relevant to compare the costs of providing a satellite sound broadcasting service with those of providing a similar service by terrestrial means. It should be noted that the digital system may provide a higher quality service than conventional FM broadcasting. Thus, any additional value of such enhanced satellite service would need to be taken into account in any cost comparison with terrestrial means.

The magnitude of these costs, and their significance will vary from country to country and with time. Relevant cost factors include:

For a network of terrestrial transmitters:

- many transmitting sites, with transmitters, antennas, and accommodation;
- roads to provide access to them;
- power distribution or local generation to provide power to the transmitters;
- communication links from the studio centre to transmitting sites;
- staff to operate and maintain them;
- the cost of electricity is significant.

For satellite broadcasting:

- the provision and launch of a satellite together with provisions for back-up in the event of failure;
- one earth station, comprising the feeder-link transmitter and facility for TTC (telemetry, tracking and command - the functions needed to establish and maintain correct operation of the satellite)), which could possibly be situated at the studio centre, obviating the need for extra roads, power distribution and communication links;
- less staff;
- the feeder-link transmitter requires very little power compared with a network of broadcast transmitters.

In either case, the listening public must have suitable receivers and suitable programme material must be available.

System characteristics also affect the cost of receivers. This is one of the reasons why the first studies considered FM with characteristics identical to those in common use for terrestrial VHF broadcasting. Nevertheless, the development of digital systems which are readily amenable to mass production will help to contain receiver costs.

One way to reduce costs is to share the satellite, and thus the space-segment costs, with other services. Possibilities include:

- providing sound broadcasting to more than one country, each having individual national or sub-national coverage;
- providing additional revenue-earning services (e.g., data) which are unrelated to sound broadcasting;
- sharing the same spacecraft with other services such as FSS, MSS, etc.
- any combinations of the above.

Such possibilities would be facilitated by the development of suitable transmitting antennas which can provide more than one beam without significant increase in size and weight. An example is an array antenna with multiple beam ports.

2.11 Receiver complexity

The frequency modulation systems and those using simple digital techniques require only conventional receivers using well-known technologies. For conventional FM using the same modulation parameters as terrestrial VHF broadcasting one would only require to add to the existing receiver a simple frequency translator from the satellite operating frequency for the VHF broadcasting band. The advanced digital systems necessitate more complex signal processing techniques in the receivers (coherent demodulation, programme selection, Viterbi decoding, sound decoding). All these operations can nonetheless be done in future with integrated circuits manufactured in large quantities and hence of low cost.

Indeed, the experimental system described in Annex IV already utilizes large-scale C-MOS integrated circuits to perform complex coding and decoding functions.

2.12 Conclusions

The results of this study suggest that satellite sound broadcasting systems in band 9 could be realized with current technology for all areas ranging from the easiest case of rural equatorial areas to the most difficult case of urban areas at high latitude.

Three types of systems have been studied. The first model uses FM with parameters compatible with terrestrial FM broadcasting and provides monophonic reception in the case of portable and mobile receivers or stereophonic reception in the case of permanent installations where obstructions can be minimized and larger antennas can be used. Alternatively, one can use companded FM with reduced audio-bandwidth and deviation, although this signal is not receivable on conventional FM receivers. The second model uses digital modulation and can provide a wider range of facilities independent of the type of reception. The third model corresponds to advanced digital systems in which special coding, interleaving techniques and/or spatial diversity reception serve to reduce the effects of fading caused by multi-path propagation.

The most stringent service requirements are best satisfied using systems especially tailored for the purpose. Examples include the two advanced digital systems which offer a higher standard of service with reduced power and p.f.d. requirements compared to a simple digital system operating under the same conditions. In other circumstances however, a simple digital or analogue FM system would be adequate and appropriate.

All the digital systems offer the choice of providing a stereophonic service to all types of receiver (mobile, portable and fixed), with the flexibility to re-apportion the capacity, if desired, to provide two or more monophonic or data channels. The complexity of digital systems should not be regarded as a barrier to implementation or penetration of the service since such systems are readily amenable to integrated-circuit realization with attendant cost savings in mass production.

The bandwidth required for a satellite sound broadcasting service in band 9 depends on the modulation method and on the extent of coverage overlap. Studies performed by the EBU and ESA for almost the whole of Africa and Europe, and by Canada in Region 2, arrive at a required bandwidth of 9 to 11 MHz for providing one national sound broadcasting programme per country when this is transmitted by frequency modulation. Simple digital modulation tends to require a somewhat larger bandwidth.

With an advanced digital system, it is nonetheless possible to broadcast up to 16 stereophonic programmes with national coverage to each country, in a total band of 84 MHz as found in a study made for Europe.

Before a satellite-sound broadcasting service could be introduced, a revision to the Table of Frequency Allocations of the Radio Regulations would be necessary in order to make either an exclusive or a shared allocation to the service.

In general it is not easy for a satellite-sound broadcasting service to share a frequency band with other services, and for this reason an exclusive band allocation would be preferred. It can be argued that this arrangement would ultimately lead to the most efficient use of the spectrum when many satellite sound broadcasting systems have been introduced. Nevertheless, sharing on the basis of geographical separation is possible in certain circumstances, especially for low-p.f.d. systems. The discrimination provided by the receiving antennas of the terrestrial services to be protected was found to greatly improve the geographical sharing situation when those services are in areas with high elevation angles to the satellite. The designation of a relatively wide shared band within which adequate segments could be used, subject to varying constraints, might provide a flexible alternative means to implement satellite sound broadcasting systems.

3. Systems for band 7*

It should be noted that the Radio Regulations do not provide for the use of satellite transmissions in this band.

3.1 *Introduction*

Transmissions in this band depend on the reflection and refraction properties of the ionosphere to extend the service area beyond that which is served by the ground wave. There are many variables associated with the use of the ionosphere which are a function of operating frequency, time of day, season, solar activity and geographical latitude and longitude. To provide the desired grade of service in the presence of these variables, it is common practice to simultaneously transmit a single programme in different bands and on multiple channels within the same band, often resulting in congestion and poor service quality.

The application of satellite techniques might lead to better utilization of the allocated bands. The ionospheric conditions which permit penetration of the ionosphere by satellite emissions can, in certain conditions, preclude long distance terrestrial transmissions, particularly above about 15 MHz.

* Section 3 with Table XVI was not accepted by all administrations at the Interim Meetings of Study Groups 10 and 11 (1983).

The concept of using satellite techniques for sound broadcasting in band 7 is not new. This concept was actively studied within the CCIR until the early 1970s and the results may be found in Report 215-2 (New Delhi, 1970). These studies showed the need for high RF power (of the order of 200 kW) which was due, in part, to the unavailability of spacecraft transmitting antennas with appreciable gain. In the context of the then existing state-of-the-art in satellite technology and launch vehicle capability, the technical and operating characteristics of satellite sound broadcasting systems operating in band 7 were formidable requirements which challenged the technological feasibility of the application. However, recent work within the United States of America on the development and the reduction of weight of large space antennas [Freeland, 1982] and associated technology shows promise. Nevertheless, considerable further study is required before the feasibility at an acceptable cost can be demonstrated.

3.2 *Quality objectives and suitable modulation methods*

It is common practice in HF broadcasting to specify a median field strength within the service area as opposed to specifying a test tone-to-unweighted noise at the output of a fully specified or standard receiver. In keeping with this practice it is deemed sufficient to specify a field strength objective to be equalled or exceeded over the service area.

It is assumed that amplitude modulation will be used because of the large numbers of AM receivers presently in use and for the foreseeable future. To provide an acceptable quality of service to low-cost portable HF receivers in a noisy radio-frequency environment requires that the median field strength be of the order of 50 dB(μV/m) to 60 dB(μV/m). The system example given in § 3.5 assumes 60 dB(μV/m) for the required median field strength.

3.3 *Technically suitable frequencies*

Ionospheric propagation effects are the key technical elements in identifying suitable frequency bands for satellite sound broadcasting. Pending further propagation and interference studies, it is believed that 15 MHz may be the lowest suitable frequency during night-time hours and during periods of low sunspot activity. The suitability would increase with frequency, and frequencies up to 26 MHz could be received by HF broadcast receivers.

3.4 *Propagation factors*

Trans-ionospheric propagation of satellite emissions in band 7 is a function of the complex dielectric properties of the ionosphere and their temporal and spatial distribution. These properties cause Faraday rotation, scintillation, absorption, reflection and refraction of electromagnetic waves traversing the ionosphere. The ionosphere is influenced primarily by solar radiation. As a result, the characteristics of the ionosphere exhibit diurnal, seasonal and solar cycle variations.

Report 725 describes the properties of the ionosphere, and Report 263 describes the ionospheric effects on Earth-space propagation.

Shielding of the Earth by the F layer and to a lesser extent by the sporadic-E layer is the most detrimental effect the ionosphere can have on satellite transmissions. The conditions for which the ionospheric penetration occurs and for what periods of time are factors determining the feasibility of satellite sound broadcasting in band 7. These conditions have been studied and are reported in detail in [Phillips and Knight, 1978].

3.4.1 *Shielding by the F layer*

Penetration of the F layer by geostationary-satellite emissions in the 26 MHz band is such that a sound broadcasting service could be provided to latitudes as great as 55° on 90% of the days around local noon. This service availability would be realized during periods when the smoothed sunspot number (R_{12}) is as high as 100.

3.4.2 *Shielding by the sporadic-E layer*

Shielding by sporadic E is expected to occur for less than 1 to 5% of the time during the summer season, and for small percentages of time for the other seasons.