REPORT ITU-R BO.955-3

SATELLITE SOUND BROADCASTING TO VEHICULAR, PORTABLE AND FIXED RECEIVERS IN THE RANGE 500-3 000 MHZ

(Question ITU-R 93/10)

(1982 - 1986 - 1990 - 1994)

1. Introduction

This Report provides information on the technical characteristics of satellite sound broadcasting systems for individual reception by vehicular, portable and fixed receivers in the frequency range 500-3 000 MHz.

Digital satellite sound broadcasting systems for reception by fixed receivers in the 12 GHz band are described in Recommendation ITU-R BO.712.

In Resolution No. 505, the WARC-79 invited the ex-CCIR to continue and expedite its studies on the technical characteristics of a satellite sound broadcasting system for individual reception by portable and automobile receivers in the frequency range 500-2 000 MHz. WARC ORB-85 considered this matter and issued Recommendation No. 2 calling for further studies on satellite sound broadcasting.

WARC ORB-88 also considered this matter and issued Resolution No. 520 which extended the upper end of the frequency range of interest to 3 000 MHz and invited the ex-CCIR to conduct technical studies on:

- the impact of choice of frequency on system parameters, especially satellite power requirements, the characteristics of transmitting and receiving antennas, and on propagation characteristics;
- the bandwidth required by the service; and
- the technical aspects of sharing between services with special consideration to geographical sharing.

The initial studies were based on conventional analogue systems. During the period 1986-1990 new studies were undertaken in the United States and within the EBU, mainly in the area of advanced digital techniques for UHF satellite sound broadcasting.

On the basis of all these studies a technical report was prepared by the ex-CCIR JIWP WARC-92 for submission to WARC-92. A more detailed report was also prepared by ex-CCIR JIWP 10-11/1. These reports present clear evidence that the provision of a satellite sound broadcasting service with complementary terrestrial broadcasting to vehicle and portable receivers is feasible with the current level of technology.

In the present report, different analogue and digital techniques are considered with their relevant link budgets showing some trade-off between service quality, service continuity, transmitted power and receiver complexity.

The ITU-R studies have been carried out in response to Question ITU-R 93/10 by a number of administrations, including Canada, Japan, France and the United States, in all three ITU Regions. These studies have provided clear evidence that the provision of satellite sound broadcasting services to vehicular and portable receivers is feasible with the current level of technology. In particular, digital systems using advanced modulation techniques and bit-rate reduction for source coding can cope well with the multipath characteristics of the satellite channel, while preserving good spectrum efficiency and minimizing the requirements for satellite transmitting power.

2. Services and systems

2.1 Service objectives

The objective of new sound broadcasting services is to improve the availability, quality and diversity of programme services to listeners. Wide area coverage will bring programme service to many listeners for the first time and advanced digital techniques will allow high quality sound equivalent to the quality available from other sound media (e.g. compact discs). Advanced digital techniques will also make possible a wide range of new programme-related and independent services with minimal impact on spectrum and power requirements. The sound BSS is aimed at fixed, vehicular and portable reception.

It is expected that the concepts and systems described below will help meet these objectives if an appropriate frequency band is allocated. The technical system objectives are determined by two factors: quality and reliability.

Quality

The service objectives for satellite sound broadcasting may play an important role in determining the type of system to be used and the overall system design and cost. Careful consideration needs to be given to the interaction between performance and economic factors. Satellite sound broadcasting has been under consideration now for over 25 years, and during that time the reproduction and transmission of sound has undergone considerable development. So too have the expectations of the listeners. Most people in urban areas now expect to listen to high-quality stereo sound, even from portable or vehicular radios. The enormous advances in the performance of domestic "hi-fi" equipment, culminating in the extensive use of compact discs, has conditioned many people to expect sound quality greater than that which even fixed FM receivers can give. Even in remote areas, similar expectations often exist, owing to the wide availability of good quality cassette recorders and compact disc players. The level of quality may be established for the most demanding listening condition (i.e. home hi-fi listening environment), while it is expected that vehicular and portable receivers will have the possibility of adjusting the dynamic range of the sound signal for comfortable listening in noisier environments such as in a car.

Much of the wide-area coverage is currently achieved by long-, medium- and short-wave ionospheric transmissions. Even though the population of these areas may prefer to receive entertainment broadcasts of the highest technical quality, it may be more economical for this type of service to accept monophonic service of medium quality provided it is reliable, and could be received on portable/mobile receivers.

For these reasons, quality objectives range from grade 3 on the 5-point ITU-R scale for a simple monophonic system to grade 4.5 for an advanced digital system. For the advanced digital systems, the objective is to provide a high-quality stereophonic service, comparable to compact disc quality. These distinct grades of service quality may lead to different system trade-offs, but in all cases are likely to lead to somewhat similar requirements in terms of frequency spectrum for sound BSS.

The size of the coverage area is also an important factor in setting the system parameters. New sound broadcasting services should allow much flexibility in providing the service to a country. It should go from local coverage of a city to regional, national and supra-national coverage depending on the needs of individual administrations. The small service areas would be best served by terrestrial broadcasting whereas large service areas would be best served by satellite broadcasting. In practice it is expected that both large and small coverage areas will exist in a given country leading to a possible co-existence of both satellite and terrestrial sound broadcasting services.

An addition to the need by many countries to provide comprehensive radio coverage over very wide areas, some nations desire a sound BSS implementation to provide specialized programme services relevant to relatively small national audiences over such wide areas. The wide area coverage achievable by sound BSS distribution will improve the economics of reaching such dispersed specialized audiences, thus making such specialized programme services more practical.

Availability

Traditional methods of planning for terrestrial broadcasting have used an availability criterion which requires 50% of the locations within the coverage area to meet the quality objectives for at least 50% of the time. It can be expected that the service availability objective for all services will be increased; and particularly for the high-quality-grade service it will need to be substantially increased from the criterion stated above.

Some possible techniques for increasing service availability under certain conditions include time diversity, frequency diversity, and space diversity at the receiver, in addition to the use of terrestrial repeaters to fill in shadowed areas in which case transmitter space diversity translates into time diversity at the receiver (described below).

2.2 Service concepts

A new generation of sound broadcasting systems is needed to provide reliable wide area and high-quality-service to portable and vehicular receivers which are now becoming the major means of receiving radio services. Both satellite and terrestrial delivery means are considered feasible and desirable for this service. When both are provided it would be economic and practical for the general public to have access to both satellite and terrestrial services with the same receiver.

The development of new sound-broadcasting services through satellite broadcasting, terrestrial broadcasting and even through an integrated satellite/terrestrial broadcasting service will take place depending on the type of service to be implemented (i.e. local, regional, national and supra-national). The development of these services would be hindered without suitable and adequate spectrum allocations and the adoption of emission standards on a regional or worldwide basis.

2.2.1 Satellite broadcasting (sound BSS)

Service areas are covered by satellite beams. The extent of the beam coverage needed on the Earth determines the size of the satellite transmit antenna. The transmission power at the satellite has to be large enough to compensate for propagation losses and to provide adequate fixed, portable and vehicular reception on the Earth. The car receiving antenna, which has to be omni-directional at least in the horizontal plane, provides for a rather limited gain (e.g. 5 dB at best). A large propagation margin (e.g. typically 15 dB; Rice or Rayleigh model) needs to be included in the link budget to cover for the cases of attenuation, blockage and selective fading due to multipath which is more pronounced in cities. Special channel coding and modulation techniques using frequency interleaving have been developed to counter frequency selective fading, thereby allowing a decrease of typically 5 dB (e.g. 10 dB; log-normal model) in the power requirement at the satellite.

2.2.2 Sound BSS with terrestrial gap-fillers (hybrid)

The satellite coverage can be improved by the use of terrestrial low-power gap-fillers. One approach to implement this concept is based on a co-channel satellite/terrestrial type of operation. This concept can be implemented by digital system A. The satellite coverage is improved through the use of low-power retransmitters using the same carrier frequency to cover shadowed areas produced by large buildings, tunnels, valleys, etc. as is illustrated in Fig. 1. These retransmitters are called "gap-fillers". This concept is a special application of the new advanced digital modulation schemes suited to operate in a multipath environment by either cancelling echoes or making constructive use of these echoes. In such case, active echoes deliberately introduced by co-frequency repeaters to fill the shadowed areas could be corrected as if they were passive echoes.

This can be done under certain restrictions related to maximum propagation delays as a function of transmitted symbol duration. These propagation delays translate physically into distances from retransmitters beyond which these active echoes would become destructive, as illustrated in Fig. 2. The use of such gap-fillers can result in a reduction in the required propagation margin from the flat fading characteristics of urban areas (e.g. 10 dB) to typically the flat fading characteristics of rural areas (e.g. 5 dB). The satellite can then be designed to provide just sufficient signal strength to cover near line-of-sight conditions typical of reception in rural areas since terrestrial repeater stations, working at the same frequency, will boost the signal in areas where an extra propagation margin is required. The retransmitted e.i.r.p. can be very low, in the order of a few watts, depending on the size of the shadowed area to be covered and the degree of isolation than can be achieved between the receiving antenna and the transmitting station of the gap-filler.

FIGURE 1

Co-channel gap-filling technique

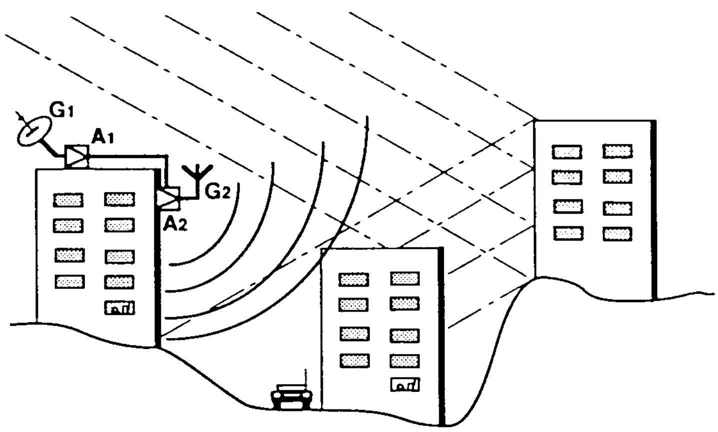
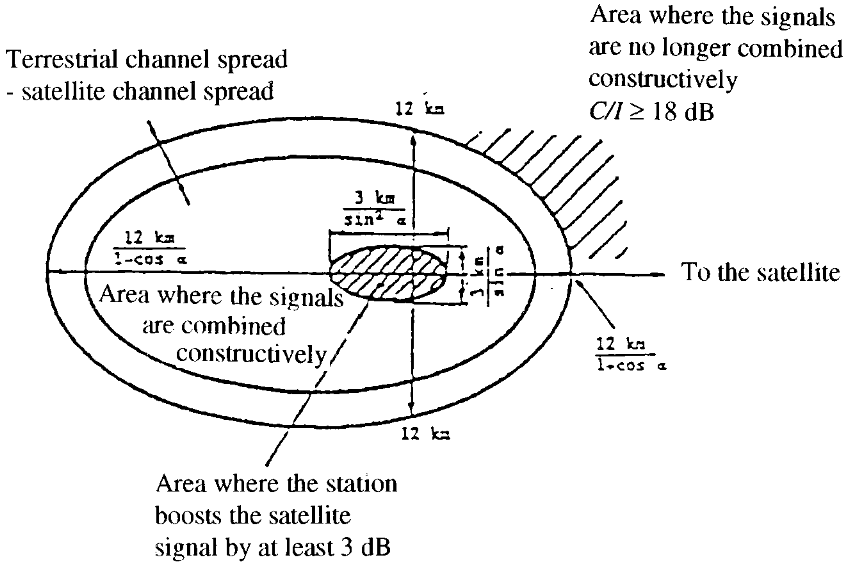


FIGURE 2

Areas around a co-channel terrestrial gap-filler station, when assuming free-space attenuation and a guard interval of 32 μs



A second approach is based on the use of different carrier frequencies by gap-fillers to retransmit in shadowed areas. In this case, no constraint would exist in terms of size of coverage area and isolation between receiving and transmitting antennas, but it would require more channels and would imply automatic tuning in the receivers to switch to local gap-filler frequency. In case of multiple gap-fillers, the same frequency reuse scheme as for terrestrial broadcasting would need to be used.

Some aspects of the use of on-channel terrestrial repeaters (gap fillers) to supplement Sound BSS warrant elaboration.

Gap fillers for hybrid satellite services need to be carefully planned so as not to destructively interfere with the parent satellite service. The situation is rather different for parent terrestrial services as in the terrestrial case, the signal level from the parent station is likely to be relatively high beyond the boundaries of the gap to be filled.

The design of gap fillers to supplement satellite services is more complex. Because the field strength from the satellite is very small it imposes a power limitation on the use of gap filler transmitters if continuous coverage is being sought. These considerations tend to limit the coverage range of individual gap fillers to considerably less than the limit of constructive symbol combination.

In practice, it would appear that individual gap fillers for satellite services will be typically limited to quite short coverage distances, perhaps about 3 km.

One solution to providing on-channel coverage for larger areas is to use several gap fillers with overlapping service areas, all fed from a common satellite service. The coverage distance of each individual gap filler must be less that the intersymbol interference distance for any other gap fillers whose coverage overlaps with that gap filler. Also, the coverage of these multiple gap fillers needs to be planned so that the field strength and path length delay around the periphery of the group of gap fillers does not result in destructive interference with the parent satellite service.

2.2.3 Satellite and terrestrial sound broadcasting in the same frequency band to the same receiver (mixed)

This concept is based on the use of the same frequency band by both satellite and terrestrial broadcasting services. It can potentially provide for improved service flexibility through the use of a common receiver. It can also maximize the spectrum use by allowing these two broadcasting services to closely coordinate their service development rather than attempting sharing of the frequency by totally unrelated services. The assumption is that the same channel and source coding would be used for terrestrial and satellite broadcasting and that with the required near omni-directional receiving antenna, the receiver would capture the emissions of both satellite and terrestrial services. Using modern technology, the same modulation techniques need not be used for terrestrial and satellite transmissions into the same receiver. However, a common modulation technique would reduce receiver complexity and costs.

All channels not allocated to BSS for a service area could be used for terrestrial broadcasting in this service area subject to the usual co-channel reuse factor and adjacent channel rejection in the receivers. Certain precautions will need to be exercised in implementing such mixed satellite/terrestrial broadcasting service where the edge of coverage of a terrestrial system is situated near the edge of a satellite coverage area assigned to the same channel. This would likely occur near the border of the service area. In this case, an isolation distance will be required to prevent interference into the adjacent country's satellite service area. In the reverse direction, if the same size terrestrial coverage area is to be maintained, the power of the terrestrial broadcasting station will need to be increased to compensate for the additional interference it will receive from the nearby satellite coverage area since the satellite pfd levels are not expected to fall off rapidly immediate to the edge of its coverage area.

Such reuse, for terrestrial broadcasting, of the channels of adjacent satellite beams of other countries, or within the same country, maximizes the spectrum usage and provides a flexible way by which a service could evolve from strictly local terrestrial broadcasting to mixed satellite/terrestrial services when wide area national services by satellite are added. This reuse could also evolve from national (or even supra-national) services carrying national interest programming by and/or specialized services over satellite later complemented by local terrestrial services when this is more economical. This could also be attractive for the future implementation of specialized commercial services over satellite for national coverage when the receivers have reached a high level of penetration.

The underlying assumption on which the above concept is based is that the same receiver can capture emissions from both the satellite and the terrestrial services. This concept of mixed satellite/terrestrial sound broadcasting leads to better and more flexible service evolution, better spectrum usage, as well as more practical and economical options for the public.

A study was made on the practical implication of such additional interference from the nearby satellite beam (CCIR, 1990-1994, Doc. 10-11S/128). It is assumed that the geostationary satellite is on the same channel as the terrestrial service and uses the same type of modulation. It is also assumed that this interference is seen by the receiver as additive uncorrelated white Gaussian noise, therefore adding to the thermal noise level in the receiver. It is found that, using the RARC-83 co-polar reference pattern for the satellite antenna, the apparent noise increase in the receiver is less than 1 dB for a receiver located beyond a relative angle seen from the satellite of $\phi/\phi_o = 1.4$ where ϕ_o is the half power beamwidth. The apparent noise increase becomes 3 dB at $\phi/\phi_o = 1.2$ and 7 dB at ϕ/ϕ

$_o$ = 1. Obviously, if the terrestrial DSB service is to preserve its coverage, the power of its transmitter has to be increased by the corresponding amount. In physical distances, the example shows that a 3

dB apparent increase in noise corresponds to a distance of about 500 km from the edge of a satellite beam of 1°. Obviously this distance can be reduced if beam shaping producing sharper roll-offs is used on the satellite.

2.2.4 Satellite and terrestrial sound broadcasting in the same frequency band with terrestrial retransmitters (mixed and hybrid)

This concept is similar to the one described in the previous section but includes the use of terrestrial retransmitters for both satellite and terrestrial services. This implies that the type of modulation used allows operation in a multipath environment and makes use of or corrects for passive as well as active echoes. The use of gap-fillers to improve the satellite coverage allows a decrease in the satellite link margin and thus in the required satellite pfd at the Earth's surface, therefore reducing by the same amount the pfd required from the terrestrial transmitter in an adjacent country using the same frequency.

The use of retransmitters either as gap-fillers or coverage extenders to improve the terrestrial coverage would allow a further decrease of the required terrestrial transmitter power and, in addition, create a sharper discrimination profile towards the country using the same frequency for satellite reception. The same sharper discrimination profile could be used to reduce the separation distance between two terrestrial transmitters using the same frequency, thus allowing greater frequency reuse. An even sharper discrimination profile could be produced through the use of highly directional transmitting antennas.

Two critical cases of adjacent channel interference can be identified for this system scenario. A receiver trying to receive a satellite channel while in close proximity to a terrestrial transmitter emitting on the adjacent channel would have major difficulty in discriminating from the adjacent channel because of the large signal level differential. This can be corrected by retransmitting the satellite channel from the same tower at a fraction of the terrestrial transmitter power corresponding to the ability of the receiver to discriminate from the adjacent channel interference. This fraction will depend much on the filtering and linearity of the receiver front end.

A receiver trying to receive a terrestrial channel while in close proximity of another terrestrial transmitter emitting on an adjacent channel would have the same difficulty to discriminate from the adjacent channel because of the signal differential created by the ratio of the two distances. The signal would either need to be retransmitted by this second transmitter, or the two transmitters would need to be co-located, or a separation distance would be required as in the case of conventional FM planning. The co-location alternative is indeed the most elegant one. Gap-fillers and coverage extenders using different frequencies would not be constrained by distance but would require more channels.

In summary, the use of terrestrial retransmitters results in a reduction of the satellite power as well as a reduction of the power of the main transmitter of the terrestrial service. It also increases the spectrum efficiency by producing a sharper gain profile at the edge of the coverage area, leading to a reduced distance between terrestrial coverage areas using the same frequency and a reduced isolation distance on the border of countries reusing terrestrially the channel of the adjacent country's satellite service.

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.

3.1 Propagation models

For moderate satellite elevation angles, it is known (see Annex 2) 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], [Jongejans, et al, 1986] and [Lutz et al, 1986] suggest that for the purpose of analysing the performance of advanced digital satellite sound broadcasting systems using forward error correction coding, that the satellite-to-vehicular propagation path may be modelled 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 § 4.1 of Annex 2.

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).

The detailed consideration of propagation characteristics and link margins, including experimental results, for satellite links in the frequency range 500 - 3 000 MHz is given in Annex 2.

4. 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;
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.

4.1 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 4, however, the condition that is 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 4.

From measurements carried out in Canada in the 1 500 MHz range, described in § 4.3 of Annex 2, it appears that an RF channel bandwidth of around 2 MHz would provide sufficient frequency diversity to cope with flat fading in various environments.

4.2 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 principle 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 3 describes the design and performance of a system based on the use of time diversity.

4.3 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.

5. 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 is digital and uses a series of advanced techniques to reduce the bit rate and, above all, to guarantee reception in the presence of fading caused by multipath propagation.

5.1 FM systems

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 frequency converter at the input stage.

The same carrier deviation and the same pre-emphasis are assumed as well as the same stereophonic 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.

In the ETS-V propagation experiment in Japan, statistical data on received power, fade and non-fade duration have been obtained [Hase, et al., 1991; Matsumoto, et al. 1992; Obara and Wakana, 1992]. The results indicate that blockage and shadowing by trees, buildings and terrain are more serious causes of impairment than multipath fading, and link margin of several dB to combat such channel impairments may not be sufficient. The multipath measurement was carried out in the dense urban area in Tokyo by using signal with 3 MHz bandwidth and elevation angle of 47 degrees [Arakaki, 1992]. This study also indicates that the coherence bandwidth derived from delay spread is about 1 MHz in the worst case.

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. For such a system, serving a heavily wooded or urban environment at high latitudes, the pfd required significantly exceeds that for digital systems.

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.

5.2 Digital systems

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 2) 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, 1986-1990, Docs. 10-11S/7(JIWP 10-11/1) and 10-11S/2 (EBU)]. 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, 1986-1990, Docs. 10-11S/2 (EBU) and 10-11S/9 (France)]. 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, 1986-1990, Doc. 10-11S/52 (United States)]. 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 information on digital systems are given below. Summary descriptions are given in Annexes 3 and 4.

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.

5.2.1 Digital System A (see also Annex 3)

Digital System A is specifically designed to overcome the frequency selectivity of the channel, so it is well suited for vehicular reception in urban environments [CCIR, 1986-1990, Docs. 10-11S/2 (EBU) and 10-11S/9 (France)]. 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;
- source bit rate per stereophonic sound programme: 256 kbit/s for subjective quality indistinguishable from "CD quality";
- modulation: 4-PSK with differential detection;
- channel coding: frequency interleaving and convolutional code of rate 1/2 constraint length 7 and free distance 10;
- noise bandwidth: about 2 MHz;
- number of useful carriers: 256;
- useful symbol period: 128 μs;
- total useful bit rate: about 1.6 Mbit/s;
- number of stereo channels: 6;
- minimum E_b/N_o: about 8.0 dB.

5.2.2 Digital System B (see also Annex 4)

Digital System B is designed to provide another solution to the propagation environment encountered by radio receivers in an urban, vehicular environment. It is based on:

- efficient source sound encoding with substantial bit-rate reduction;
- choice of audio quality from true, stereo "CD" quality at 384 kbit/s to rates as low as 32 kbit/s;
- convolutional channel coding with Viterbi decoding at either 1/2 or 1/3 code rate;

- improved receiver operation in difficult reception environment of fading, standing waves and echoes.

6. Link budget

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 (ITU-R quasi peak), weighted, in the case of 50 μs pre-emphasis, or a slightly higher value for 75 μs pre-emphasis.

For 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.

For Digital System A, the required E_b/N_o in a Gaussian channel for a bit-error ratio (BER) of 10^{-4} is about 6 dB, using differential demodulation and average code rate of 1/2. For BER = 10^{-3} the required E_b/N_o is about 5.8 dB.

In the Rayleigh channel, E_b/N_o is typically about 11 dB for BER = 10^{-4} (9.5 dB for BER = 10^{-3}).

With the use of coherent demodulation the required E_b/N_o figures could be reduced to about 4.5 - 5.0 dB. The improved performance of coherent demodulation may permit a reduction in satellite transponder power requirements of up to 3 dB thereby allowing a doubling of the number of services for a given satellite bus.

6.2 Receiving antennas

Receiving antennas for stationary (fixed), 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.

Receiving antennas for pocket-size portable receivers

Hand-held satellite receivers are now available for the global positioning system (GPS). They typically use a 5 to 10 cm long quadrifilar helix design for near-hemispherical coverage. In the case of small portable receivers, it is hard to secure reliable gain due to losses caused by the proximity of the human body. A suggestion is to mount a helical antenna on the headset where such gain variation would be largely alleviated. This means however, a dedicated and bulkier headset. The gain will likely be restricted to 2-3 dBic* towards the satellite and 0 dBi at horizon.

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* dBic refers to dB relative to isotrophic circularly polarized source.

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 has been done [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, 1986-1990, Doc. 10-11S/51 (United States)].

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 omni-directional 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.

Mixed satellite/terrestrial reception

Reception of satellite and terrestrial transmissions with the same receiver as in the case of a mixed satellite/terrestrial service using the same frequency band, if considered at the outset, may result in minimal increase in complexity of a common receiving antenna. Typically, low cost antennas achieving a gain of 5 dBic towards the satellite and 0 dBi in the horizontal direction are achievable. Two alternatives for antenna structure exist: tall and thin mast antennas similar to current whip antennas and low profile printed antennas. In the case of the mast antenna, a quadrifilar helix design with a circularly polarized conical pattern optimized for a given elevation angle (6 dBic peak gain) is suggested with typically 1 cm diameter and 30 cm long. This antenna could still give reasonable gain in the horizontal plane (0 dBi). The second preferred alternative is a low profile printed antenna based on a circularly polarized loop structure producing a conical pattern. A peak gain of 6 dBic over a bandwidth of 8% is feasible at 45° with a 21 cm diameter antenna with a thickness of 1.5 cm. However, the size increases rapidly when the gain has to be maximized for a lower elevation angle. The gain in the horizontal plane (> 0 dBi) would be achieved by either a simple $\lambda/4$ monopole (5 cm) or a patch in the centre of the circular flat antenna which would be remotely switchable with the channel selection on the receiver. More complex antenna structures exist (e.g. mechanically or electronically steerable antennas) which can provide higher gain towards the satellite and the horizon. The use of active antennas will allow a reduction of the size of these antennas with performances comparable to current larger passive antenna implementations.

6.3 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 2.

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 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.

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

Case E: This case applies to the digital systems 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 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 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 areas needs to be included (see Annex 2).

In the case of a hybrid system, the link margin can be reduced to 5 dB for an elevation angle of 20°-30°, because terrestrial gap-fillers are used to cover the gap on the satellite coverage area. When using a highly inclined elliptical orbit satellite the margin can even be reduced to 3 dB for an elevation angle above 60°.

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.

6.4 Link budgets for various systems

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

6.4.1 FM systems

Table 1 shows the link budgets for the two FM system examples with the various link margin Cases A, B, C and D as defined in § 6.3. 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 pfd 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 pfd values are -123.4 dB(W/m^2) and -114.1 dB(W/m^2), respectively.

TABLE 1

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 dB Hz)				180 (= 52.6 dB Hz)			
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 and antenna noise temperature	K	75 + 180				75 + 180			
Receiver figure-of-merit	dBK^{-1}	-19.4				-19.4			
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)	$dB(W/m^2)$	-131.8	-122.8	-112.8	-104.8	-122.5	-113.5	-103.5	-95.5
Equivalent field strength at edge of beam	dB(μV/m)	14.0	23.0	33.0	41.0	23.3	32.3	42.3	50.3
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	33.6	43.1	53.1	61.1	42.9	52.4	62.4	70.4
Transmitter power for 1° beamwidth	dBW	-10.3	0.8	9.2	17.2	-1.0	8.5	18.5	26.5

(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.

6.4.2 Digital Systems A and B

An example of the link budget for Digital Systems A and B operating at 1 GHz, at the elevation angle of 17° and for a 1° beamwidth, is given in Table 2. The link margin (i.e. the fade allowance) of 5 dB is taken into account, given that, in urban areas, the satellite system is supplemented by terrestrial gap-fillers or repeaters.

TABLE 2

Link budget for BSS (Sound) (Digital Systems A and B)

SYSTEM	A	B	Units
Operating frequency	1.0	1.0	GHz
Polarization	circular	circular	
Channel error protection	Conv. (R=1/2)	Conv. (R=1/2)	
Useful bit rate per channel[1]	256	256	kbit/s
Required E_b/N_o for 10^{-4} BER	7.0[2]	3.3[3]	dB
(Theoretical) downlink C/N_o	61.1	57.4	dB Hz
System implementation margin	2.0[4]	0.0	dB
Hardware implementation margin[5]	2.0	2.0	dB
Degradation due to uplink	0.4	0.4	dB
Interference allowance[6]	2.0	2.0	dB
Required downlink C/N_o	67.5	61.8	dBHz
RECEIVER			
Receiving antenna gain	5.0	5.0	dB
Antenna noise temperature[7]	105	105	K
Coupling and filter losses[8]	1.0	1.0	dB
Receiver noise figure	1.0	1.0	dB
Receiver figure-of-merit	-19.4	-19.4	dB
PROPAGATION			
Fade allowance[9]	5.0	5.0[10]	dB
Line-of-sight pfd at edge of beam (-3 dB)[11]	-115.2	-120.9	dBW/m^2
Spreading loss (elev. = 17°)	163.0	163.0	dB
SATELLITE			
e.i.r.p. on axis[12]	50.8	45.1	dBW
Satellite antenna gain for 1 beam	44.4	44.4	dB
Satellite antenna input power for	6.4	0.7	dBW
1° beam and one stereo programme	4.4	1.2	watts

Note 1 - The current range of output data rates for source codes consistent with a 4.5 sound impairment factor is between 180 kbit/s and 256 kbit/s per stereo programme. Further bit-rate reduction is projected in the future.

Note 2 - Theoretically and experimentally verified for Digital System A. A reduction to approximately 4.5 dB is possible if coherent demodulation is used.

Note 3 - Value for System B not yet verified by tests.

Note 4 - Comprises 1 dB allowance for the 20% guard interval of Digital System A and 1 dB equivalent loss caused by Doppler shift in a vehicle moving at 100 km/h. This allowance needs to be increased with frequency.

Note 5 - Some improvement may be expected with advanced high-volume manufacturing.

Note 6 - Allowance in the link budget for interference resulting in 15.5 dB aggregate interference protection ratio allowing large frequency reuse for BSS Sound. For System A interference protection ratio can be reduced by a further 1 dB to 14.5 dB when allowance is made for the fact that interference received during the guard interval is not to be taken into account. When considering the effects of interference on performance, some useful information may be obtained by preparing separate link budgets based upon two limiting cases. These are firstly where the interference fades equally with the wanted signal and secondly where the interference level remains unfaded while the wanted signal fades. Practical operation of a Sound BSS system will represent a statistical mix of these cases.

Note 7 - Includes thermal noise from the surroundings, man-made noise and sky noise due to oxygen and water vapour in a suburban environment (based on Report ITU-R F.285, suburban case, and Report ITU-R SM.670, residential case), taking into account the directivity of the receiving antenna.

Note 8 - Larger filter loss may need to be assumed for operation in bands close to that used by high-power services to allow for use of high rejection and sharp roll-off filters. Total losses from Receiver Coupling, Filter Loss and Hardware Implementation may be reduced by 1.5 to 2 dB through performance improvements and the low probability of these factors aggregating concurrently.

Note 9 - This fade allowance is considered adequate for outdoor reception of a satellite signal in rural and suburban environments. This figure is recommended for use in satellite-link budget calculations as the margin to be provided at the edge of the coverage area. Gap fillers or repeaters will be required to supplement the reception in urban environments as described in § 2.2.2.

Note 10 - Assuming that this system (subject to verification) allows for the use of on-channel terrestrial gap fillers or repeaters.

Note 11 - Satellite beam designs in the region of 1.5 GHz may provide a coverage area defined by a signal level at the edge of coverage 2.0-2.5 dB below the peak beam power with a consequential reduction in the satellite transponder power required.

Note 12 - In determining the overall performance of Sound BSS, allowance needs to be made for the satellite transponder back-off required to ensure adequately linear performance. In the absence of practical measurements or simulations, a transponder back-off of 2.5 dB might be an appropriate value for preliminary calculations assuming a linearized TWTA transponder.

7. 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:
  - 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:
  - 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 examples in the present Report assume a carrier frequency of 1 GHz. Section 13 of this Report (cost considerations) indicates that the initial investment cost for the satellite-based transmission delivery system for a 1° beam is significantly greater at both 750 MHz and 2 400 MHz compared with 1 500 MHz. For a 3° beam the costs at 750 MHz are comparable with those at 1 500 MHz, but the costs at 2 400 MHz remain significantly greater than those at 1 500 MHz.

In Resolution 520, WARC ORB-88 extended the possible frequency range for the broadcasting-satellite service (sound) to the range 500-3 000 MHz.

Table 3 shows a comparison of system parameters as a function of frequency between 0.5 and 3 GHz, including the required satellite power and the distance between the terrestrial gap-filler transmitters in a hybrid system.

TABLE 3

Variation of system parameters as a function of frequency for Digital System A (similar values apply to Digital System B)(1)

Parameter	Unit	0.5	1.0	1.5	2.0	2.5	3.0
Frequency (GHz)		0.5	1.0	1.5	2.0	2.5	3.0
BSS on-channel gap-filler coverage radius for C/I = 15.5 dB (2, 3)	(km)	10.0	5.0	3.3	2.5	2.0	1.7
BSS fade allowance relative to fade at 1 GHz (= 55 dB)	(dB)	-1.5	0.0	1.1	2.1	2.9	3.7
Effective receiving antenna aperture relative to that at 1 GHz (antenna gain = 5 dBi)	(dB)	+6.0	0.0	-3.5	-6.0	-8.0	-9.5
Receiving system noise temperature	(dB(K))	26.2	24.4	24.1	24.0	24.0	24.0
Beamwidth = 1° Sat. power(4)	(W)	13	49	134	292	550	940
Beamwidth = 1° Ant. diam.	(m)	43	21	14	11	9	7
Beamwidth = 1.6° Sat. power(4)	(W)	34	126	344	750	1410	2400
Beamwidth = 1.6° Ant. diam.	(m)	27	13	9	7	5.4	4.5
Beamwidth = 3.5° Sat. power(4)	(W)	164	600	1650	3600	6700	11500
Beamwidth = 3.5° Ant. diam.	(m)	12	6	4.1	3.1	2.5	2.0
Distance between omnidirectional BS on-channel coverage extenders(2, 3)	(km)	30.0	15.0	10.0	7.5	6.0	5.0
BS fade allowance relative to fade at 1 GHz (= 10 dB)	(dB)	-2.9	0.0	2.2	4.1	5.8	7.3
Effective receiving antenna aperture relative to that at 1 GHz (antenna gain = 0 dBi towards horizon)	(dB)	+6.0	0.0	-3.5	-6.0	-8.0	-9.5
Receiving system noise temperature	(dB(K))	26.2	24.4	24.1	24.0	24.0	24.0
ERP(6) of main transmitter: cov.rad. = 33 km; E = 100 m(5)	(kW)	0.8	4.2	15	40	92	190
ERP(6) of main transmitter: cov.rad. = 50 km; E = 150 m(5)	(kW)	5.8	30	106	285	650	1300
ERP(6) of main transmitter: cov.rad. = 64 km; E = 150 m(5)	(kW)	53	272	960	2600	5900	12100

Note 1 - The values in this table are consistent with the link budget and the assumptions given in Table 2.

Note 2 - For system parameters resulting in equivalent loss of 1 dB caused by Doppler shift in a vehicle moving at 100 km/h.

Note 3 - The coverage radius can be considerably higher in the case of repeaters using different frequencies but more spectrum will be required as discussed in § 2.2.

Note 4 - Powers are for a 12* stereophonic programme multiplex assuming hybrid implementation.

Note 5 - E = Effective height above average terrain of the transmitting antenna.

Note 6 - Terrestrial station ERPs are for a 12* stereophonic programme multiplex. They correspond to the same receiver system noise temperature as for the satellite case but with 0 dBi antenna gain, 3 dB interference allowance and no allowance for the feeder-link noise contribution are assumed. The ERPs were calculated referenced to the centre of the UHF frequency band, using the F(50,50) propagation curves for 10 m above ground level. A correction factor of 11 dB was applied to bring this height to 1.5 m, more typical of vehicular reception. ERPs at higher frequencies were obtained through frequency scaling assuming the square root of the ratio of frequencies based on fade allowance of 10 dB at 1 GHz. The applicability of this scaling to terrestrial broadcasting requires further study.

8. 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 the range 500 - 3 000 GHz. In particular, the satellite antenna diagrams used at WARC-77 are considered to be feasible in this frequency range, [CCIR, 1986-1990, Doc. 10-11S/53 (USA)]. Better side-lobe rejection will be possible by the use of fast roll-off antennas. Further details are given in Table 4.

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* For a Digital System A multiplex that contains six stereophonic sound programmes, the values for powers are divided by 2.

TABLE 4

Deployable satellite antenna types suitable for use in the 1 - 3 GHz region

Structure	Category	Construction and aperture deployment method	(m)	Frequency limit (GHz)
Ribs with mesh surface	Radial rib	Umbrella-like	4.5	12
	Wrap-rib	"Carpenter tape" ribs unwrapped from central column	9	6
	Cable-catenary	Mesh supported radial booms and catenary cables	4.9	0.2
	Fan-rib	Ribs, open like a fan, to form segment of a circular aperture	4.5	6
Hoop with mesh surface	Hoop-column hoop-frame	"May-pole" structure	15	0.8*
Truss with mesh surface	Tetra-hedral (i.e. "box") truss	Multiplicity of connected cubes with mesh supporting stand-offs of appropriate length (box deployed by energy stored in "carpenter-tape" hinges)	4.6	-
	Quadrature aperture	Hoop-column concept forming four, H independent apertures	3.5 each	(model only)
	Geodesic truss	Triangular pyramids (element of classical geodesic structures)	5	12
	Prism	(Details not available)	10	1
	Tension truss	Cable-stiffened mesh support structure	20	2-20
Inflatable	Multi-layer fabric	Positive gas pressure throughout life, or inflated structure, rigidized by solar heat	3.5	-

* Technique applicable to much higher frequencies.

9. Total service bandwidth estimation

The total bandwidth required by the service is governed by the following factors:

- The width of the radio frequency channel multiplied by the number of channels per service area. In the case of Digital System A (COFDM), a channel corresponds to the width of the frequency block used to broadcast a number of stereophonic radio programmes.
- The number of such channels which is necessary to give a service to every country or service area; this factor depends on the necessary protection ratio. For a digital system, this protection ratio is usually the result of a compromise between noise and interference. As for a satellite service, the available power on board is a critical parameter, the protection ratio is taken to minimize the necessary C/N. On the contrary, for terrestrial service the protection ratios can be decreased [CCIR, 1986-1990, Doc. JIWP10-11/1-44 (Canada)].

In the case of the down link, it is not possible to obtain frequency reuse through the use of the other hand of polarization.

Also, because a receiver antenna has little directivity, discrimination between different orbital positions is not possible.

9.1 FM systems

About 10 MHz are necessary to provide one national sound broadcasting programme per country. This study is valid for monophonic as well as stereophonic reception. The latter will, however, only be achievable with permanently-installed receivers.

To provide 12 stereophonic programmes per country, 120 MHz are necessary.

9.2 Digital systems

Different studies have been made to estimate this number of channels and consequently the total frequency bandwidth required.

EBU studies

In the case of COFDM, the width of the frequency block should be large enough to overcome the frequency selectivity of the channel. The different carriers associated with a given programme should be well separated in frequency so that they are decorrelated and do not fade simultaneously. It has been demonstrated that a frequency block (including guard bands) of about 1.75 MHz is technically adequate and provides a capacity of up to six high-quality stereophonic programmes. The number of channels necessary to cover a number of service areas can be determined by developing coverage scenario exercises and will, of course, depend on the assumptions made for coverage and for protection ratios.

In Europe, EBU has developed a computer program which generates examples of coverage scenario exercises. These exercises are based on the following assumptions:

- The WARC-77 diagram of the satellite antenna considered as feasible at 1 GHz.
- A co-channel protection ratio of 15 dB and an adjacent channel protection ratio of 6 dB.

The main results of this study are summarized in Table 5.

TABLE 5

Coverage scenario	National	Supranational	Pan European
Number of beams	35 (Europe) or 70 (Europe and Africa)	11 (Europe)	1 (Europe)
Number of blocks per country (1 block = 1.75 MHz, i.e. up to six stereophonic programmes)	2	2	2
Channel reuse factor	16	8	1
Total frequency bandwidth (MHz)	56	70(1)	105(2)

Note 1 - To give each country one block, an extra number of channels equal to approximately 12 channels are needed.

Note 2 - To give one block to each of the 30 countries covered.

From the technical point of view, the possibilities of frequency reuse decrease when the sizes of the beams increase. At the other extreme, with very small beams, frequency reuse becomes more difficult because of the larger number of beams and the multiplicity of the interferers. Taking account of the power limitation which makes very large beams impractical, it seems that for a continent like Europe, there is a technical optimum of the beam size, which is in the range of 1°-1.5° corresponding approximately to national coverage.

Canadian studies

In Canada, a study was made to estimate the spectrum requirement for the mixed satellite/terrestrial digital sound broadcasting service (see § 2.2 on the service concept).

In this study, it is estimated that Canadian terrestrial digital sound broadcasting needs alone could be met with 48 MHz of spectrum. It is estimated that with this amount of spectrum it would be possible to provide each existing AM and FM broadcasting station with one stereophonic programme channel and also to include an allowance for future growth. Furthermore, to take into account the Canada/United States border effect, an additional 25% of spectrum would be required, which would correspond to 48 MHz + 12 MHz = 60 MHz of terrestrial spectrum.

Concerning the satellite broadcasting spectrum requirements, the results of the study are summarized in Table 6.

TABLE 6

Coverage scenarios	Uniform circular beams	Canada	North America*
Number of beams	large	8	17
Channel reuse factor	4	6	9
Bandwidth required per service area (24 stereo programmes) (MHz)	8	8	8
Total spectrum requirement (MHz)	32	48	72

* Assumes eight beams for Canada, four beams for continental United States and one for Alaska, two beams for Mexico and two supranational beams for the Caribbean or a larger number of small beams for that area.

Table 7 combines these two requirements.

TABLE 7

Combined coverage scenarios

Coverage scenarios	Uniform circular beams	Canada	North America*
Spectrum for sound BSS (MHz)(1)	32	48	72
Spectrum for sound BS (MHz)	48	48	60
Extra BSS channels for compatibility in the same country (MHz)	8	8	8
Extra BSS channels for compatibility with adjacent country (MHz)	-	-	8
Total spectrum requirement (MHz)	56	56	76

* Assumes eight beams for Canada, four beams for continental United States and one for Alaska, two beams for Mexico and two supranational beams for the Caribbean or a larger number of small beams for that area.

Note 1 - Based on the provisions of 24 stereophonic programmes to each service area. If only 12 stereophonic programmes per service area is assumed then the BSS spectrum requirement would be approximately halved. However, the total spectrum requirements would remain approximately the same due to the BS requirements.

It is interesting to note that the spectrum requirement for the mixed satellite/terrestrial service is just slightly larger than the requirement for terrestrial broadcasting alone, a result that indicates the spectrum efficiency obtained by employing the mixed terrestrial/satellite implementation concept.

USSR studies

The USSR has made studies:

- to estimate the frequency requirement for sound BSS in the territory of the USSR;
- to estimate the frequency requirement for sound BSS in the territory of European countries.

If the necessary bandwidth of the frequency block is assumed to be 4 MHz (within which 16 stereophonic sound programmes are assumed), then to implement a satellite sound broadcasting system in the USSR would require an 80 MHz bandwidth.

Assuming the same needs of stereophonic programmes per country for 34 European countries, this study shows that 130 MHz would be required.

United States studies

Four BSS(S) systems have been proposed to the Federal Communications Commission (FCC) for construction permits [ITU, 1993, Doc. 10-11S/154 (United States)]. The systems will use portions of the 2 310 - 2 360 MHz frequency band allocated for BSS(S) in the United States for domestic broadcasting.

A summary of the numerical values each system developer has chosen for several key factors related to the design of the space segment is as follows:

	System			
	I	II	III	IV
Overall spectrum requirement (MHz)	10	16	25	50
Spectrum requirement per listening area (MHz)	5	16	8	25
Number of satellites per system	2	2	1	2
Main downlink antenna diameter (m)	3	3	20	3
RF output per satellite (kW)	1	1	1.8	1.2
Downlink e.i.r.p. per beam at EOC (dBW)	62	57	57	52
Maximum pfd (dB(W/m^2/4 kHz))	-132	-136	-126	-128
Effective link margin (dB)	5.2	16*	14**	4

* The developer of System II bases its estimate of the large effective link margin for System II on the condition that simultaneous broadcasting of each programme will be made from each of two satellites at different radio frequencies, and that the satellites will be positioned 30° apart in geostationary orbit, thereby providing a form of space, frequency and time diversity using two independent wavefronts arriving from different directions as seen by the receiver and the nearby environment.

** For spot beams, the margin varies from approximately 8 to 14 dB, depending on the elevation angle to the satellite.

The primary difference, from a space segment standpoint, among these designs is that System III will use a 20 m S-band antenna to permit the formation of 31 small spot beams of approximately 330 km diameter at the half-power points, as compared to approximately 3 m S-band antennas for the other three systems.

Further details on each system is available [ITU, October 1993, Doc. 10-11S/154 (United States)].

10. Feeder links

10.1 Characteristics of the feeder links to the BSS (Sound)

The main characteristics of the feeder links to a sound BSS are the following:

- polarization discrimination can be used to reduce the total frequency bandwidth required;
- the earth station transmitting antennas have a high directivity and high gain. The higher the directivity, the smaller the orbital separation required to allow frequency re-use. The

directivity increases with frequency, but this can require the implementation of a tracking system on the earth station transmitting antenna;

- the availability of the feeder link should not affect the down-link service quality. This parameter has a direct impact on the power requirement at the earth station depending on the frequency range.

10.2 Total bandwidth required

The total bandwidth required depends on the selected orbit (highly-inclined elliptical orbits or geostationary-satellite orbits) and on the strategy of the distribution of satellites on orbital locations.

The choice of the frequency band for the feeder link will determine whether polarization discrimination is available. In such a case, the total frequency bandwidth could be reduced by a factor of two. Furthermore, the directivity of the up-link antenna will allow discrimination between closely spaced satellites.

Additionally, the amount of spectrum required for the feeder links is determined by the number of channels (or blocks) that can be transmitted by a satellite. This is dependent on the satellite antenna diameter and the satellite maximum RF power capability. Considering these parameters, a 10 m satellite antenna and 1.5 kW RF power can be available in the near term, and a 20 m satellite antenna and 2.5 kW, respectively, are achievable in the longer term.

Studies [CCIR, 1986-90, Doc. JIWP 10-11/1-41 (Canada)] assuming Digital System A have shown that for the near term, the maximum amount of feeder link spectrum that can be used on one satellite is limited by the above constraints to 30 MHz for down links at 0.5 GHz, reducing to 4 MHz for down links at 3 GHz, regardless of the down-link spectrum capacity required. The same holds true for the long term for frequencies of 1.5 GHz and 2 GHz where the maximum spectrum is 44 MHz and 18 MHz, respectively, while for frequencies around 1 GHz and below, the maximum spectrum is determined by the number of down-link beams that can reuse the same frequency.

10.3 Suitable frequency band

According to RR 22, the FSS includes the feeder links to other satellite services and, in particular, the feeder links to the BSS.

Taking into account the high availability required for the feeder links, the frequency band must not be too high.

11. Sharing considerations

Studies of the feasibility of sharing frequencies between the BSS (Sound) and services with primary allocations in the frequency range 500 - 3 000 MHz have concentrated primarily on the conditions that would protect these services against interference from BSS systems. In nearly all of the cases considered, such protection will require significant geographic separations between the boresight of the BSS (Sound) service area and the receiving stations in the existing services.

The magnitude of the geographic separations required will depend on many factors, including the size of BSS service area, the angle of arrival of the BSS signal, the BSS system configuration (e.g. the extent to which complementary terrestrial repeaters and transmitters are included in the system), the specific BSS (Sound) system parameters, the parameters and sharing criteria of the systems in the services with which frequency sharing is considered, the operating frequency (which determines the satellite e.i.r.p.), and other considerations.

Depending, in particular, on the service interfered with, the e.i.r.p. of the BSS (Sound) satellite, and the angle of arrival of the interfering signal, the geographic separations required to protect interfered-with services range from 200 km to over 7,000 km. In certain specific cases, required geographic separations may even approach zero. Since a typical BSS (Sound) service area may have a radius of about 600 km, this implies that in some cases systems of other services may be located within the BSS (Sound) service area. However, interference to the BSS (Sound) from the other service then becomes dominant. The size of the area in which such interference to the BSS receivers will occur depends on the characteristics of the interfering system in question.

To reach more definitive conclusions regarding frequency sharing, interference to BSS (Sound) receivers would have to be considered for each specific system. For this purpose, additional information is needed on the full range of system parameters associated with the systems which might provide a BSS (Sound) service and, on the parameters of the systems of other services actually implemented in the frequency band it is proposed to share.

In view of the number and geographical distribution of receiving stations already implemented in the existing services of many countries, the relatively large geographic separations required for their protection would not generally be achievable in practice.

Therefore, an exclusive allocation for the BSS (Sound) may be preferred, in which case complementary terrestrial sound broadcasting uses within such an allocation would also be practical.

However, if the BSS is not implemented in certain areas, the existing services may be able to continue the use of the band. Furthermore, depending on the actual BSS (Sound) channel frequency assignment implementation, there may be improved scope for band sharing using frequency separation within specific BSS service areas.

It can be assumed that the terrestrial broadcasting (sound) service will not have as serious interference effects on fixed radio systems as the BSS. In this regard, § 6.4.8 of the ex-CCIR Report to the WARC-92 describes studies Canada has carried out to determine the required separation distances when sharing between terrestrial digital sound broadcasting and point-to-multipoint radio systems.

In the following sections, details are given on some of the sharing situations.

11.1 Sharing between BSS (Sound) and point-to-multipoint systems

According to the study conducted by Canada, sharing between BSS (Sound) and point-to-multipoint systems in the fixed service may be possible with certain geographical separations ranging from several hundred kilometers to beyond the satellite horizon. Necessary separation distances depend upon the BSS system parameters and the maximum permissible interference power to point-to-multipoint systems.

It should be noted that the uniform interference limit used in the study provides adequate protection to meet recommended ITU-R performance standards. When considering special applications of point-to-multipoint systems to rural local networks where other alternatives are not economically viable, a higher interference allowance (e.g. interference-to-noise power ratio of 0 dB) may be appropriate, geographical separation distances being reduced accordingly.

11.2 Sharing between BSS (Sound) and point-to-multipoint systems in the fixed service

Studies conducted by the United States and Japan have shown that power flux-density limits equivalent to the specifications stated in RR 2557 are suitable to protect point-to-point radio-relay systems in the bands 1 710 - 2 500 MHz. However, sharing studies reported in Report ITU-R BS.955-2 show that geographical separations ranging from hundreds of kilometres to over 9,000 km, depending on the BSS (Sound) system parameters, would be required in order to meet these power flux-density limits.

It may be assumed that point-to-point digital radio-relay systems with multi-hops and utilizing regenerative repeaters on each hop could have more relaxed interference criteria by allocating most of the design objectives of performance degradation to the worst hop, and thus the additional discrimination required for sharing might be reduced in such cases.

11.3 Sharing with the mobile service

A preliminary analysis has shown that frequency sharing between aeronautical telemetry and one proposed BSS (Sound) system within the same service area produces mutually harmful interference (see also § 16.8 of the ex-CCIR Report to the WARC-92).

In general, sharing with the mobile service requires large geographic separation ranging from approximately 500 km to more than 7 000 km.

11.4 Sharing with passive and active microwave sensors

Spaceborne passive microwave sensors measure soil moisture, salinity, sea surface temperature, rain, snow, ice and sea state. Ocean salinity measurements, for example, need an interference threshold of -165 dBW in a reference bandwidth of 100 MHz (Reports ITU-R SA. 693 and ITU-R SA.694).

Calculations made using the methods in Report ITU-RR SA.850 show that the interference power generated by a sound-broadcasting satellite (advanced digital system) and received by a spaceborne passive microwave sensor is 33 dB above the harmful interference level. It can be concluded that sharing between passive sensors and broadcasting satellites (sound) is not feasible in the frequency range 500 - 3 000 MHz.

A modern synthetic aperture radar (SAR) has a sensitivity of about -130 dBW in a receiver bandwidth of about 15 MHz. Report ITU-R SA.695 states that the maximum noise-like interference for the SAR is determined by the saturation point of the receiver which was found to be at least -115 dBW. The interference power from 16 channels of satellite sound broadcasting, each with an e.i.r.p. of 50 dBW could be as high as -132 dBW, below the harmful interference threshold for the SAR.

The e.i.r.p. of a typical SAR is of the order of 67 dBW, 17 dB greater than the 50 dBW that a broadcasting satellite (sound) might employ. Since the SAR is located in a low earth orbit (as low as 500 km) as compared with the 37 000 km orbit for a broadcasting satellite, the interference level into an earth terminal receiver could be as much as 50 dB higher than the desired signal. It can be concluded that receiving earth stations in the BSS would be subject to unacceptable pulse type interference and that sharing would therefore not be feasible.

11.5 Protection of the radioastronomy service

The radioastronomy service (RAS) cannot share with the broadcasting-satellite service (BSS) or with the terrestrial broadcasting service when the radioastronomy antenna is within line-of-sight of the transmitter. This is because these active services transmit power flux-density levels that produce signals several orders of magnitude greater than the receiver noise levels in those services. For the RAS, power levels of signals that produce harmful interference are typical of the order of 10^{-3} times the system noise level (see Report ITU-R RA.224). Thus BSS and broadcasting signals exceed harmful interference thresholds for radioastronomy typically by a factor of 10^6, even when the interfering signals are received in the far side lobes of the radioastronomy antenna. The factor by which the interference exceeds the harmful threshold is sufficiently great that sharing is generally impossible regardless of the specific details of these communications services or the frequency range involved.

Due to the high power-flux densities employed by transmitters in the BSS, harmful interference to the RAS may also be caused by band-edge interference. Careful control of the radiated spectrum can alleviate problems of band-edge interference. Annexes II and III to Report ITU-R RA.697 describe some techniques to minimize band-edge interference to stations in the RAS.

11.6 Sharing with space research, EESS and space operation services

Information concerning sharing with the SRS, SOS and EESS in the bands 2 025 - 2 110 MHz and 2 200 - 2 290 MHz may be found in § 13.3.4 of the ex-CCIR Report to the WARC-92. Protection criteria for the SRS (deep space) may be found in § 11.4 of the same Report.

11.7 Sharing with ISM

It is apparent from the somewhat limited data available that emissions from microwave ovens in the industrial, scientific and medical (ISM) bands, would represent a potential source of interference to BSS (Sound) reception by fixed, vehicular and, particularly, indoor portable receivers within the band 2 400 - 2 500 MHz. The greatest difficulties would be encountered around the centre frequency of 2 450 MHz with the likelihood of the occurrence of interference diminishing as each end of the band is approached.

A particular case in which a sound BSS system is susceptible to interference arises in and adjacent to the band 2 400 - 2 500 MHz. This band is designated by Footnote 752 of the Radio Regulations for industrial, scientific and medical (ISM) applications, and radio services operating within the band must accept harmful interference which may be caused by such applications. A primary ISM use of the band is for household microwave ovens.

Measurements of interference to a COFDM DAB prototype receiver (filter bandwidth: 3.5 MHz) from a microwave oven were made by France [CCIR Doc. 10-11S/14 (France) (1990-1994)]. The following values of C/I were obtained for just perceptible degradation of the sound in the COFDM receiver:

Wanted input signal level (Note 1)	Microwave oven interferences: signal level for just perceptible degradation (Note 2)
-77 dBm	-41 dBm
-57 dBm	-25 dBm

Note 1 - The prototype COFDM receiver had an input level range (-30, -90) dBm.

Note 2 - A manufactured microwave oven was used with water inside. The microwave oven spectrum was translated from 2.5 GHz to the UHF TV frequency band so that the centre frequencies of the spectrum were nearly the same.

From these results, calculations were made based on Doc. CISPR/B/WG 1 (JP), 2 July 1990, which gives a typical e.r.p. template for microwave ovens and the minimum separation distances between the microwave oven and the COFDM DAB receiver were obtained.

The results are summarized in Tables 8 and 9:

TABLE 8

e.r.p. of the microwave oven and frequency band	Minimum distance for a power at the input of the DAB receiver of -57 dBm	Minimum distance for a power at the input of the DAB receiver of -77 dBm
-8 dBW 2 400 - 2 500 MHz	3 m	17 m
-2 dBW 2 400 - 2 500 MHz	6 m	35 m

If we consider the attenuation due to the buildings (10 dB), we obtain the following values:

TABLE 9

e.r.p. of the microwave oven on the frequency band 2 400 GHz - 2 500 GHz	Minimum distance for an input level of -77 dBm and a DAB receiver outside of the building
-8 dBW	5 m
-2 dBW	11 m

Based on these preliminary measurements, it may be concluded that, in the case of a transmission of the COFDM DAB signal by satellite at 2.5 GHz, it will be very difficult to get good reception either inside or outside of buildings, because of the radiation from microwave ovens.

Further measurements must be undertaken to complete this study.

11.8 Sharing between terrestrial digital sound broadcasting and point-to-multipoint (P-MP) radio systems

Studies conducted by Canada have shown that sharing near 1.5 GHz between terrestrial (digital) sound broadcasting and point-to-multipoint (P-MP) radio systems would require certain minimum geographical separations.

Tables 10 and 11 summarize the separation distances in some examples of broadcasting transmitters.

TABLE 10*

Examples of required separation distance from digital sound broadcasting transmitter to a fixed service hub station at 1.5 GHz to protect point-to-multipoint systems

Broadcasting coverage radius	Broadcasting transmitter antenna height	Broadcasting ERP(1)		Required separation
(km)	(m)	(dBW)	(kW)	(km)
33	100	39.7	9.33	179
50	150	48.4	69.3	256
64	150	58.9	773.0	355

* New separation distance tables based on more recent information can be found in Report 1203-2.

(1) These power levels have been converted from those used for the standard 10 m receive antenna height to the power required for antenna heights of 1.5 m which are more typical of vehicular reception by the addition of 11 dB in each case.

TABLE 11*

Examples of required separation distance from a fixed service hub station to digital sound broadcasting transmitter to protect the broadcasting coverage area

Broadcasting coverage radius	Broadcasting transmitter antenna height	Broadcasting ERP		Required separation
(km)	(m)	(dBW)	(kW)	(km)
33	100	39.7	9.3	141
50	150	48.4	69.3	158
64	150	58.9	773.0	172

* New separation distance tables based on more recent information can be found in Report 1203-2.

11.9 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 kilometers.

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.

Several administrations are considering sound-broadcasting services, both for terrestrial and satellite services in the same geographic area. A potential conflict between satellite services and terrestrial services can be minimized by ensuring that the receivers offer both large dynamic range and low-noise figures.

Section 8 of the present Report deals with satellite transmitting antenna technologies and indicates that better side lobe rejection will be possible in the future by the use of fast roll-off antennas and that the reference pattern used at the WARC-77 to plan the BSS as 12 GHz, suitably translated into the 500 - 3 000 MHz range, could be realistically assumed.

Table 12 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 reuse by other services.

TABLE 12

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 discrimination (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	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 13.

TABLE 13

Summary table of the situations and required separation distances

Sound BSS system	Interfered with service	Permissible pfd for sound BSS	Required isolation (dB)	Minimum separation distance for 1° beam (km) Elevation angle (degree) at the terrestrial receiver		
				5	30	60
Conventional FM (Case A) (-111.1 dB(W/m^2)) (-111.1 dB(W/(m^2 · 4 kHz)))	Broadcasting - maximum protection - minimum protection Fixed Mobile - low elevation angle	 -138 dB(W/m^2) -128 dB(W/m^2) -154 dB(W/(m^2 · 4 kHz)) -147.9 dB(W/(m^2 ·30 kHz))	 10.9-26.9 0.9-16.9 32.9-42.9 36.8	 3404 2717 9570 6741	 1510 1181 3652 4827	 676 199 2728 ---
Companded FM (Case A) (-120.4 dB(W/(m^2))) (-120.4 dB(W/(m^2 · 4 kHz)))	Broadcasting - maximum protection - minimum protection Fixed Mobile - low elevation angle	 -138 dB(W/m^2) -128 dB(W/m^2) -154 dB(W/(m^2 · 4 kHz)) -147.9 dB(W/(m^2 ·30 kHz))	 1.6-17.6 0 - 7.6 23.6-33.6 27.5	 2749 2151 5693 3124	 1208 668 1529 1631	 264 0 981 ---

TABLE 13 (CONTINUED)

Sound BSS system	Interfered with service	Permissible pfd for sound BSS	Required isolation (dB)	Minimum separation distance for 1° beam (km)		
				Elevation angle (degree) at the terrestrial receiver		
				5	30	60
Digital (Case F)* (-109 dB(W/m^2)) (-126 dB(W/(m^2 · 4 kHz)))	Broadcasting - maximum protection - minimum protection	 -138 dB(W/m^2) -128 dB(W/m^2)	 13.0-29.0 3.0-19.0	 3171 2810	 1567 1260	 736 361
	Fixed	-154 dB(W/(m^2 · 4 kHz))	18.0-28.0	3140	1363	861
	Mobile - low elevation angle	-156.7 dB(W/(m^2 · 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.

* Worst-case represented by stand-alone sound BSS system (i.e. no support from gap fillers).

11.10 Conclusions on sharing

Studies of the feasibility of sharing frequencies between the BSS (Sound) and services with primary allocations in the frequency range 500 - 3 000 MHz, have concentrated on the conditions that would protect those services against interference from BSS systems. In nearly all of the cases considered, such protection will require significant geographic separations between the boresight of the BSS (Sound) service area and the receiving stations in the existing services.

The magnitude of the geographic separations required will depend on many factors, including the size of the BSS service area, the angle of arrival of the BSS signal, the BSS system configuration (e.g., the extent to which complementary terrestrial repeaters and transmitters are included in the system), the specific BSS (Sound) system parameters, the parameters and sharing criteria of the systems in the services with which frequency sharing is considered, the operating frequency (which determines the satellite e.i.r.p.), and other considerations.

Depending, in particular, on the service interfered with, the e.i.r.p. of the BSS (Sound) satellite, and the angle of arrival of the interfering signal, the geographic separations required to protect interfered-with services range from 200 km to over 7,000 km. In certain specific cases, required geographic separations may even approach zero. Since a typical BSS (Sound) service area may have a radius of about 600 km, this implies that in some cases, systems of other services may be located within the BSS (Sound) service area. However, interference to the BSS (Sound) from the other service then becomes dominant. The size of the area in which such interference to the BSS receivers will occur depends on the characteristics of the interfering system in question.

To reach more definitive conclusions regarding frequency sharing, interference to BSS (Sound) receivers would have to be considered for each specific system. For this purpose, additional information is needed on the full range of system parameters associated with the systems which might provide a BSS (Sound) service, and on the parameters of the systems of other services actually implemented in the frequency band used.

In view of the number and geographical distribution of receiving stations already implemented in the existing services of many countries, the relatively large geographic separations required for their protection would not generally be achievable in practice.

Therefore, an exclusive allocation for the BSS (Sound) is to be preferred, and complementary terrestrial sound broadcasting uses within this allocation would then be practical. The implications for sharing between complementary terrestrial transmission of BSS (Sound) services and other services require urgent study.

12. Alternative satellite orbits

During the past two decades, operators have generally concentrated on using the geostationary satellite orbit for the transmission of satellite signals to and from Earth. Such orbits provide continuous coverage of the Earth with little satellite movement being perceived from the ground. At high latitudes the satellite is, however, seen at low elevation angles.

Satellite elevation angle is a major factor in planning systems and its impact is particularly important in northern latitudes where significant population centres are to be found above 40°N.

Recently, development has reached the stage that it has been possible to consider systems that would permit communications with and broadcast to land mobile stations or receivers. Essentially, the problem has been to compensate for the low performance of the mobile equipment, since such systems, particularly those for broadcasting, would have very large user populations and so must be kept simple. In addition, it is impossible to accommodate large antennas on the mobile station. And, with decreasing elevation, satellite blockage by buildings and the terrain start to become dominant factors in link budgets.

For these reasons a number of organizations decided to look again at the use of alternatives to the geostationary satellite orbit, taking as a starting point those orbits used for the Molniya system.

Whilst there are many classes of elliptical orbit, those studied in greatest detail are those that have most utility in Europe, which is assumed for planning purposes to have a latitude range of 35°N to 70°N. They fall into two classes which are characterized by perigee height and as a consequence whether or not they transit the Val Allen belts.

The first class of orbits, which have an equivalence to the Molniya system, have typical apogee and perigee heights of 1,500 and 39,000 km, respectively, and an orbital period of 12 h. A system based on this highly elliptical orbit (HEO) would typically consist of three satellites operational for eight hours each. All satellites would transit the Van Allen belts twice per orbit and special measures would have to be taken to protect satellite components. With such a system, elevation angles in excess of 60° could be maintained over the service area. From the geometry of the orbit, a second coverage area may be exploitable at a longitudinal difference of 180°.

In a second class of orbit, the perigee and apogee heights are respectively 26,000 and 46,000 km, giving a 24 h orbital period. In such a configuration, called "Tundra", a minimum of two satellites would be required for continuous coverage. No second coverage area is exploitable. For both classes of orbit the inclination will be approximately 63°.

A major system difference between geostationary satellites and HEO based systems arises due to the need to transfer traffic between satellites entering and leaving the satellite coverage area. The system design must achieve this handover even though it is probable that satellite range will be different for each satellite and that each satellite will have a significant and different doppler shift.

In most, if not all HEO applications, single shaped or clustered spot beams will be used. Due to the range difference over the operational period of the orbit, the coverage at the Earth's surface for a given angular antenna beam will vary.

To maintain a constant 3 dB coverage on the Earth, a reconfigurable or zoom antenna, with a variable beamwidth, is required. Alternatively, a fixed beamwidth antenna can provide a constant power flux-density over a certain range at the edge of the coverage area by using the beam-edge gain slope to compensate for the difference in path loss.

Aside from the zooming effect, certain satellite configurations, e.g., Nadir pointing, will lead to a rotation of non-circular or clustered spot beams. This effect, analogous to a slow transition between cells for a cellular system, may be unacceptable for applications where coverage is tailored to a country or a region, such as broadcasting.

Whilst a mechanical solution may be adopted to compensate for the rotation effect, phased array techniques will generally be employed to compensate for zooming effects. With a phased array, rotation could also be corrected.

As far as the link budget is concerned, the highly inclined orbits have the following advantages for high latitude countries, due to the increased angle of elevation:

- a reduction of the link margin; and
- the possibility to use a slightly higher gain receiving antenna.

12.1 European study

A study called "Archimedes" [Archimedes, 1990] has recently been conducted by the European Space Agency. A Molniya-type system has been selected for this study on the basis of lowest cost for European application. In this system, four spacecraft are placed in highly elliptical orbits inclined at approximately 63° with a 12-hour period. Each spacecraft is placed in a separate orbital plane so that the four orbital planes are spaced at 90°. Each of the spacecraft is active for six hours over the desired European coverage region, returning 24 hours later. There is an opportunity for a pilot Archimedes system to encourage industrial and service sectors with more market potential.

12.2 Slightly inclined orbits

For normal geostationary satellite designs, there may be an opportunity to reduce the overall satellite costs and/or extend their useful life by operating them in a slightly inclined orbit at some stage of their life, possibly at the beginning and end. For example, it may be advantageous to launch a satellite into an appropriate slightly inclined orbit and to operate it for a few years while it slowly drifts towards a geostationary orbit. Once it reached the geostationary orbit, it could then be maintained in that orbital location until near to its end of life. At that time it could again be allowed to drift into an inclined orbit while continuing to provide a Sound BSS service.

The main parameters to be considered when evaluating the merits of slightly inclined orbit operation are its compatibility with other services on the same satellite, changes to the satellite footprints both in pointing and coverage area and changes in the free-space attenuation due to variations in the path length.

13. Cost considerations

A direct-to-listener sound broadcasting system utilizing satellites will consist of feeder-link networks, up-link earth stations, satellites, and receivers. Apart from the radio receivers, the rest of the system can be considered to be the transmission delivery system as a unit.

13.1 Radio broadcast receivers

There are between one and two billion radio broadcast receivers worldwide, with a replacement market estimated to be around 100 million sets per year. The overall market is growing proportionally greater than the world's population growth. Further, there is a trend favouring better reception quality than is possible for the AM channels (both medium wave and shortwave).

All this indicates strongly that satellite sound broadcasting will result in a need for large quantities of receivers. Therefore, rather than low quantity production for an elite market, it appears reasonable to expect high annual production quantities (tens of millions and up), and concomitantly, competitive prices for receivers that include UHF digital reception capability.

Estimates from manufacturers indicate prices can begin (at the bottom of the model range) in the tens of US dollars for digital receivers of the type illustrated in this report. Obviously, models with expensive speakers can rise into the thousands of US dollars.

Assuming an average price of $US 200 (a mix of table model, high fidelity in the home, and car receivers), the annual sales could be in the billions of US dollars. This estimate is based on the assumption that a steady state worldwide annual market of 10 000 000 to 100 000 000 receivers will eventually occur.

The frequency modulation systems 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 digital systems necessitate more complex signal processing techniques in the receivers (coherent or differential demodulation, programme selection, Viterbi decoding, sound decoding). All these operations can nonetheless be done with integrated circuits manufactured in large quantities and hence of low cost. Indeed, the digital broadcasting systems described in Annexes 3 and 4 utilize large-scale C-MOS integrated circuits to perform complex coding and decoding functions.

13.2 Transmission delivery system

Extensive technical and cost trade-off analyses have been conducted in the United States during 1990-1991 on realistic transmission delivery systems. The assumptions on power flux density requirements reflect recent digital receiver designs and propagation measurements, and are consistent with earlier sections of this Report.

Selected findings from these trade-off analyses are contained in this section. It is clear that a properly designed satellite system will provide inexpensive delivery of high quality, high reliability sound to wide coverage areas. These costs are significantly lower than either standard AM short-wave, or terrestrial FM or medium-wave AM if the objective is to cover wide areas, and not just selected urban/suburban areas in the latter case.

The major variables considered and their ranges of variation are:

- beamwidth: 1° to 3°; a 1° beam covers approximately Poland, Germany, or Kansas; a 3° beam covers approximately India or the United States east of the Mississippi;
- audio quality: from 48 kbit/s, equivalent to monophonic FM to 256 kbit/s, equivalent to stereophonic compact disc quality, for the information bit rate;
- satellite capacity per satellite: up to 2 500 kg beginning-of-life weight and up to 6 500 watts end-of-life solar power (if a requirement exceeds either of these limits, an additional satellite is required);
- radio reception environment: portable (outdoor, most single family homes, and most buildings) and mobile (vehicular);
- transmission frequency: 750, 1 500, or 2 400 MHz.

For indoor portable (table model) reception, it was recognized that the receive antenna could have a modest gain. 8 dB was selected for 1 500 MHz, and 12 dB for 2 400 MHz. 5 dB was retained for 750 MHz.

The collection of system possibilities described in the previous paragraphs were subjected to detailed cost analysis utilizing a communication satellite cost model available at the Jet Propulsion Laboratory. Costs of all satellite system components, ground equipment, launch and insurance are included. Examples of the findings are noted below.

13.2.1 General cost findings

As a function of frequency and coverage per spot beam, required antenna size and the rf power required per channel are the major cost drivers.

Rf power required into mobile receivers increases approximately as the 2.5 power of the frequency and is the main reason why 2 400 MHz systems cost more than 1 500 MHz systems. As noted below, the total investment costs do not increase by this ratio because satellite components become smaller at the higher frequency and partially compensate for the cost of additional power.

The difference in cost between a mono-FM requirement and a stereo "compact disk" requirement is simply scaled by the ratio of bit-rate requirement, i.e. 256/48 - 5.333.

13.2.2 Specific cost findings

Figs. 3 and 4 are presented as examples of the full findings in [Golshan, 1991]. They exhibit estimated initial investment costs in four displays. Moving clockwise from the upper left, they show (1) total cost, (2) lifetime cost per channel, (3) cost per channel hour, and (4) cost ratio vs. frequency. The horizontal axis refers to coverage capacity, specifically to the number of broadcast channels for the audio quality noted per million square miles of coverage. These two figures deal with mono FM; therefore, the number of channels shown is generally relatively large. For example, using Fig. 3, which is for 3 degree beams, to cover the lower 48 states in the United States with a choice of, say, 30 mono FM channels at all locations, will require 30 by 3 million square miles. Entry into the curves in Fig. 3 on the horizontal axis would be made at 30 times 3 = 90. Carrying along with the example, a 1 500 MHz system would cost slightly under $ 100 million, with a 12-year per channel cost of around $ 1 million, an hourly cost of about $ 14. Such a system would be a little less expensive than a 750 MHz equivalent system, and a 2 400 MHz equivalent system would be about 1.5 times as expensive.

Comparing Fig. 3, 3-degree spot beams, with Fig. 4, 1-degree spot beams, shows the dramatic effect of antenna size at the lowest frequency, 750 MHz. In Fig. 3 there is not much difference in cost between a 750 MHz system and a 1 500 MHz system; in Fig. 4, the 750 MHz system costs are substantially greater than the 1 500 MHz system.

Comparing 1 500 MHz with 2 400 MHz in both figures, the 2 400 MHz system, for all but low capacity 1-degree spot beam systems has costs ranging from approximately 1.5 to 2.2 times the cost of a comparable 1 500 MHz system.

These estimated costs are for initial investment and do not include operating costs during the lifetime of a satellite. Since operating costs will be effectively independent of the chosen radio frequency, this will decrease the cost ratio between 2 400 MHz and 1 500 MHz stated in the previous paragraph. More analysis along the lines of conducting total life cycle cost estimations, including discounting of initial investment costs using reasonable interest rates, is recommended.

FIGURE 3

In-orbit space segment cost versus frequency and capacity for a 28-spot-beam, 3-degree beamwidth DBS-R system, FM-quality digital modulation

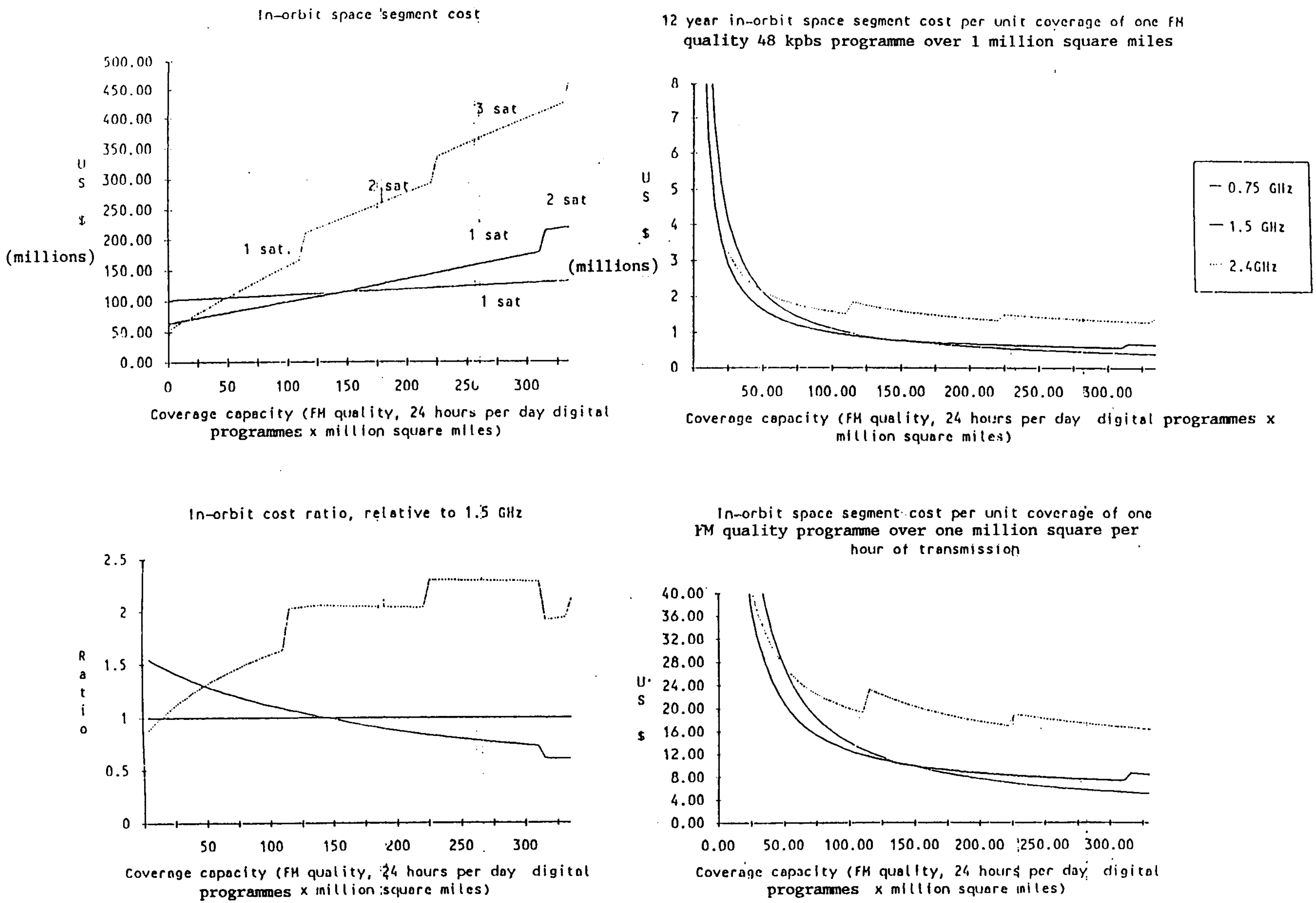
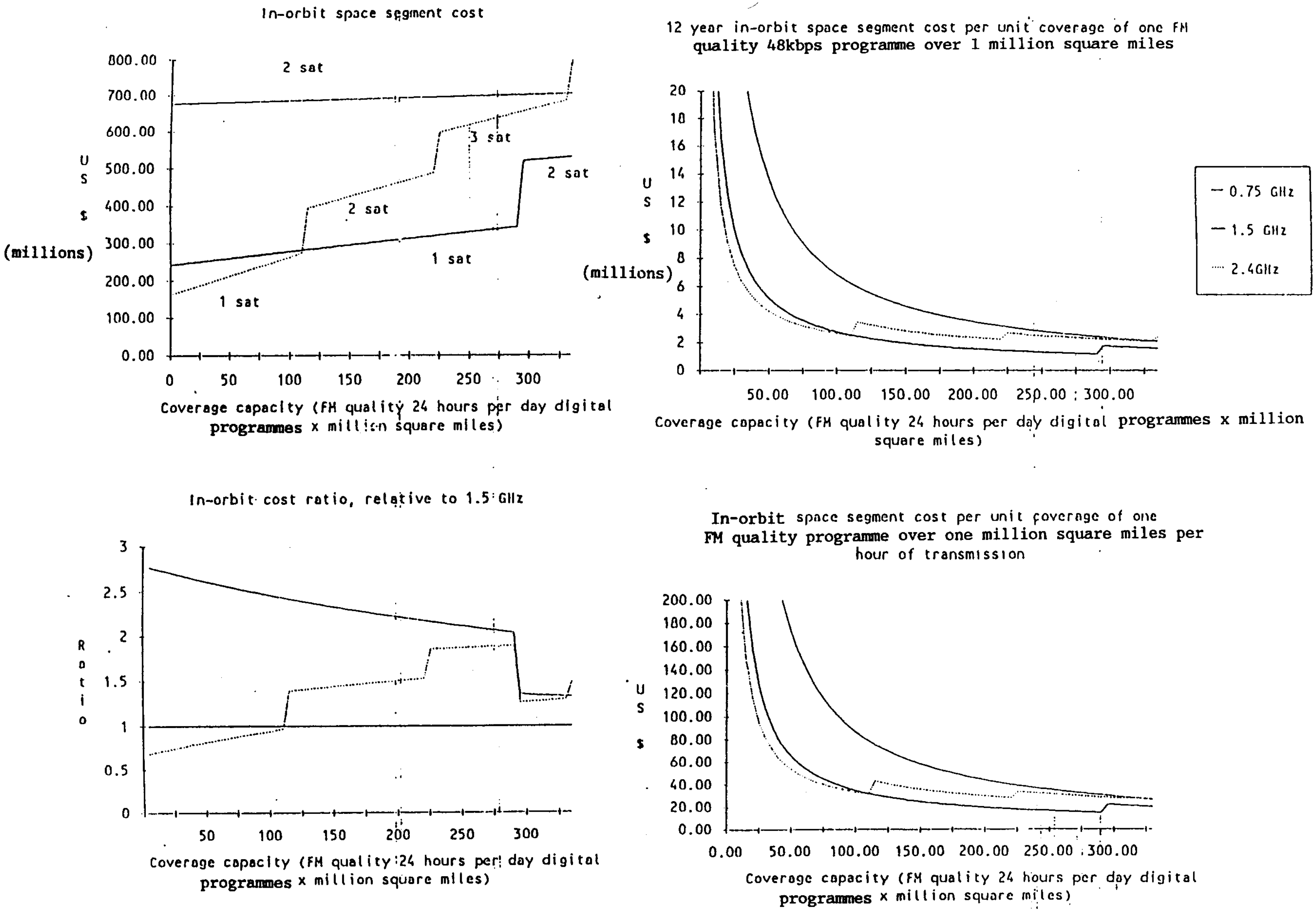


FIGURE 4

In-orbit space segment cost versus frequency and capacity for 252-spot-beam, 1 degree beamwidth DBS-R system, FM quality digital modulation



14. Experimental evidence of service feasibility

14.1 Experiments and demonstrations with Digital System A in Europe

In June 1988, the CCETT installed the first COFDM UHF transmitter at Rennes having the following characteristics:

- transmission frequency	794 MHz
- transmitting antenna height	140 m
- number of stereophonic sound channels*	16
- antenna gain in the direction of the main service area	12 dBi
- power per stereophonic sound channel at the input of the transmitting antenna	1 W
- total ERP	256 W
- ERP per stereophonic sound channel	16 W
- total bandwidth	7 MHz
- total number of useful carriers	448
- useful symbol period	64 µs
- guard interval	16 µs
- maximum path-length difference for which two signals are still combined constructively	6 km

The broadcast signal was received in an automobile equipped for mobile tests. The first successful trial runs under real conditions were conducted in cooperation with the IRT in July 1988 during preparations for the EBU’s first public demonstration of the so-called COFDM/MASCAM experimental Digital Audio Broadcasting system in September 1988 at the WARC ORB-88 in Geneva [Dosch et al., 1988].

These trial runs showed that, despite a quite large service area in which the reception was perfect, some locations in the urban area were impaired by heavy shadowing and there were some gaps in which the signal was attenuated by more than 30 dB.

At that time, the idea of using a gap-filling technique materialized, but two important questions were raised:

- How much separation (in dB) can be achieved between a directive receiving antenna and a transmitting antenna installed in a building environment when the geographical separation is in the range of 50 to 100 m?
- How will the COFDM receiver behave when it moves from the zone served by the main transmitter to that served by the retransmitting station?

* Only one channel was operated with a sound programme, the 15 remaining channels were loaded by a fixed pattern configuration. Using the most up-to-date source coding technique, a total of 24 stereophonic sound channels may be transmitted with the same total useful bit rate of 5.6 Mbit/s.

A first problem is the need to maintain correct time-coherence of the feeds, bearing in mind that the feed circuits may change. This would require exclusive lines even for gap-filling relays.

From these sound signals a synchronizing signal must be derived, sound signal and data must be multiplexed and the COFDM signal produced. All this would have to be done in exactly the same way at all transmitter sites. Although possible in principle, some form of automatic monitoring would be required to make corrections when even slight differences in modulation to those of adjacent transmitters occur. This monitoring would not seem possible because of the co-channel operation.

The sole reasonable method seems to be to have a central production of the COFDM signal. The COFDM signal in digital form would require about 12 times the data rate of a corresponding number of baseband coded sound signals. This price would have to be paid for safe and clear operation of such a network.

The cost of programme feed lines for an SFN (single-frequency network) would be greater than for feeding an FM network, particularly since the simple re-broadcast feed of relays is not possible.

An attractive cost-effective solution may be offered by using a satellite for programme distribution. A COFDM signal can be down converted to within a normal video-frequency range. For example, with a COFDM block bandwidth of about 2 MHz, up to three such packages, each containing six to eight stereo programmes, could be contained within one FM-TV transponder channel using frequency modulation. If the 11 GHz satellite band were to be used, the appropriate technology is already available from satellite TV. The low signal-to-noise requirement of COFDM compared with a television signal implies that only a small satellite receiving antenna is required.

If operating at 2.5 GHz the use of FM would not be required, thus allowing direct reception with fixed installations, but not for mobile reception. EBU studies show that for this case the power requirement are too high for mobile reception.

An additional advantage of programme distribution by satellite is that it can also be used for feeding relay stations thus avoiding the need for individual feed lines to these relays.

Thus the requirement at individual transmitter sites when fed by satellite with the complete COFDM signal as described will be confined to FM demodulation, filtering, frequency conversion and power amplification. Furthermore a similarly uncomplicated operation as with TV relays can be expected.

Besides all these advantages of programme distribution by satellite, there are some disadvantages. Firstly there is an additional delay of about 240 ms in the transmission. Secondly, and perhaps more importantly, a satellite failure results in a complete loss of all programmes. To allow comparable reliability to that of existing terrestrial services, a standby system would be required, thereby adding to the cost. Finally, there is the cost of providing the feed to the satellite earth station. This could be reduced by siting the earth station in close proximity to the combing centre.

To examine these and other points, a small single frequency network with two retransmitting stations has been installed, with the characteristics set out in Table 14. Using this complete UHF single frequency network, numerous test runs and measurements have been made, leading to the following preliminary conclusions:

- At UHF, very simple and inexpensive equipment can be used for a retransmitting station having an amplifier gain of at least 70 dB.

- Despite the relatively short guard interval used in that first experimental system (16 ms), the behaviour of the COFDM receiver remains excellent even in some exacting situations where two signals of equal power are received with a delay difference exceeding, by a few microseconds, the guard interval of the COFDM symbols.

Today, apart from a few very small areas, the whole city of Rennes and a wide area of the surrounding countryside are served perfectly, with a total transmitted power per stereophonic sound channel of only 1.1 W.

This first UHF network, which has moved some way beyond a simple experiment, has demonstrated the viability of the gap-filling technique as a substitute for an increase, by a factor of 100 or more, of the power of the main transmitter. Tests have also been conducted in the United Kingdom [Shelswell et al., 1991] with the same experimental system working from the Crystal Palace transmitting station in South London at 531 MHz. The urban terrain in the service area is more rugged than in Rennes and it was found necessary to employ gap-filling in areas which were shadowed by terrain (rather than buildings) near ground level; such conditions even occurred at locations where the main station signal was extremely strong at line-of-sight receiving heights. Nevertheless, the gap-filling technique was successful and provided good service with echo delay differences up to about 125% of the guard interval.

TABLE 14

Characteristics of two gap-filling transmitters installed in Rennes

	Station 1	Station 2
Receiving antenna gain	14 dBi	14 dBi
Transmitting antenna height	50 m	60 m
Retransmitting antenna gain	9 dBi	9 dBi
Isolation between the input of the retransmitting antenna and the output of the receiving antenna	86 dB	90 dB
Overall gain of the amplifier	55 dB	70 dB
Cable losses	5 dB	5 dB
Power per stereophonic sound channel at the input of the retransmitting antenna	2 mW	40 mW
Total ERP	250 mW	5 W
ERP per stereophonic sound channel	16 mW	313 mW

In 1991, full-scale demonstrations of digital sound broadcasting system A were given at NAB 91 in Las Vegas (Nevada, United States), the Radio Festival in Birmingham (United Kingdom), the IFA in Berlin (Germany) and Radio 91 in San Francisco (California, United States).

Both static and mobile demonstrations in a specially arranged coach were given. Nine stereo programmes were transmitted simultaneously, along with one FM programme for comparison. For example, in Las Vegas, the main transmitter was located on top of the Las Vegas Hilton Hotel and a gap-filler was located on top of the Golden Nugget Hotel in the downtown area. Some 1,500 participants took a tour on a bus. Overall, the demonstration was highly successful and showed clearly the superiority of the system over FM.

14.2 Field trials in Canada with Digital System A

14.2.1 Concept and system evaluation tests

The feasibility and potentials of digital audio broadcasting (DAB), were demonstrated across Canada, using the Eureka-147 COFDM-MUSICAM system, through an elaborate programme of laboratory and field tests, as well as nationwide (Ottawa, Toronto, Montreal, Vancouver) static and mobile demonstrations using a temporary terrestrial broadcast fixed transmitter at 798 MHz, including a simulation of satellite reception.

The following are the general conclusions:

- The trials have demonstrated that a digital audio broadcasting service is practical, that the technology works, and most importantly, that there is a public demand and industry need for this new service.
- The media, industry, and public response was enthusiastic. The reaction to the new radio broadcasting service concept and the quality of the product delivered by the COFDM-MUSICAM prototype system was very positive.
- All participants in the test programme were highly impressed by the excellent performance of the COFDM-MUSICAM sound broadcasting system in the laboratory and in the field.
- In the laboratory, the MUSICAM/COFDM system performed as per its specification.
- The listening tests showed that the MUSICAM process appears to be transparent with respect to basic audio quality. Audio material processed though MUSICAM (at 128 kbit/s per monophonic channel) was consistently preferred to high-quality FM.
- From an analysis of the data collected during the field tests, it has been concluded that the performance of the system can generally be predicted solely from the received power level.
- In spite of the relatively low transmitting powers used (considering that the equivalent of 16 stereophonic signals were being transmitted in the UHF-TV band), the actual coverage achieved was surprisingly extensive and relatively free of gaps, confirming its power efficiency and ability to cope with multipath fading.
- The effectiveness and practicality of the co-channel gap-filler concept was confirmed.
- In general, it is believed that a close-to-perfect coverage could be obtained with some minor adjustments at the transmitter end and with the addition of a few low-power co-channel gap-filler transmitters.
- Statistics on the multipath environment of the cities visited indicate that a guard interval in excess of 24 microseconds would be preferred to the 16 microsecond guard interval used in the prototype system tested.

14.2.2 Simulation of satellite reception tests with COFDM

In Toronto, the transmitting antenna was installed on the CN Tower, approximately 360 metres above ground, right in downtown. With the highly elevated transmitting point and the densely built-up and high-rise downtown core of Toronto nearby, the geometry was appropriate to a simulation of satellite reception in dense urban areas, with elevation angles from 15 to 40 degrees (the range for Canadian metropolitan cities is from 20 to 35 degrees). CBC Engineering carried out signal level measurements along the downtown streets of Toronto at points with different elevation angles. The majority of locations did not have line-of-sight with the transmitting antenna, but the DAB reception was always excellent (even directly under the CN Tower). The signal level measurements were compared to free space calculations in order to derive some values to account for building obstruction shadow loss. Preliminary results show that, for angles from 15 to 40 degrees, the measured received signal level in a 7 MHz bandwidth, is in average 15 dB lower than the free space calculated values.

14.3 Field experiments

14.3.1 Field experiments in the United States with a low data rate digital system

During September 1991 a series of experimental field tests were carried out in the United States for the first time on an experimental low data rate BSS (Sound) System [CCIR, 1990-94, (Doc. 10-11S/48)]. The experiments were conducted to assess the feasibility of good quality audio transmission via a geostationary satellite into vehicular receivers within the 500 - 3 000 MHz range.

The only way to do this at this time (1991) was to accept the power-flux density limitations of existing maritime satellites, and to fit the bit rate, and hence overall audio quality, to the limitations imposed by the satellite.

This was successfully done over a two-week period with controlled measurement procedures. The fade margin was restricted to 2 dB, and therefore heavy foliage blocked signal reception. Apart from this, audio quality for music, within a 3 kHz band, was quite good. Field tests matched closely with laboratory simulations. Audio programme content from the National Public Radio was primarily music. An analysis report was released at the end of 1991.

The main features of the broadcast system and the experimental protocol were:

Broadcast system

- Carrier frequency 1 544 MHz
- 3 kHz audio, transformed to 19.2 kbit/s (commercial vocoder)
- Channel coding with convolutional coding, time interleaving and differential modulation
- e.i.r.p. of 26 dBW
- 10 dB receive antenna on the roof of the vehicle with tracking ability
- E_b/N_o of 10 dB for good quality audio.

Experimental protocol

Data collected with variations in:

- Satellite elevation angle from approximately 10° to 40°
- Interleaving distances - none, 16 kbit/s, 32 kbit/s
- Vehicle speed

- Foliage levels - from none to heavy
- A video camera tracked the satellite at all times
- BER measurements were taken.

14.3.2 United States tests and demonstrations in Pasadena, California

The first satellite broadcast of compact disc (CD) quality, compressed digital audio, to a receiver with characteristics similar to those of Digital System B [ITU, October 1993, Doc. 10-11S/154 (United States)] for BSS (Sound) direct to listener receiving systems, took place in Pasadena, California during the week of 14-18 June 1993. The satellite characteristics, in terms of power per audio channel and the antenna beam size, were also in the range that might be used in a limited coverage area BSS (Sound) system.

The satellite used was the NASA Tracking and Data Relay Satellite (TDRS), which has two independent S-band single access (SSA) forward links in the frequency range of 2 020 to 2 123 MHz. Each link can transmit 7 Watts over a 2° beam (an e.i.r.p. of 46.47 dBW). Each beam can provide either left or right hand circular polarization and can be pointed anywhere on the surface of the Earth visible from the satellite. One of these beams was used in the Pasadena demonstration.

While this first broadcast was more a demonstration of the satellite Digital Sound Broadcasting (DSB) concept than a rigorous test, it was used to evaluate some omnidirectional receiving antenna designs and to make an initial assessment of the problems of indoor reception. It is planned to utilize TDRS for future field trials of Digital System B, which is currently being implemented into hardware.

A block diagram of the equipment used in the Pasadena test and demonstration is shown in Fig. 5. An on-orbit standby spare TDRS, positioned at 62° west longitude, was used to transmit the signal to the Pasadena area. With this geometry, the elevation angle to the satellite was 20°. Table 15 gives the parameters of the link budget. BPSK modulation was used to stay within the power-flux density (pfd) limits in this frequency band.

Two types of receiving antennas were tried during this test: the drooping dipole and the circular patch illustrated in Figs. 6a and 6b, respectively. As shown in these figures, the height of the drooping dipole is approximately 10 cm, while the diameter of the patch is 16 cm (on a .3 cm thick substrate). Both of these antennas have constant gain in azimuth, which is a desirable characteristic for mobile reception. Vertical cuts of the gain patterns for these antennas are shown in Figs. 7a and 7b.

The elevation of the beam of the drooping dipole can be changed over a limited range through a mechanical adjustment of its elements relative to the ground plane. The peak gain point was brought down to about 35° from horizontal; therefore, the antenna had to be slightly tilted to provide peak gain toward the satellite. This antenna performed better than the patch antenna and was used throughout the test.

The elevation of the beam of the patch antenna is adjusted by changing the feed points and thus the excitation mode. The TM_{41} mode which was used to bring the gain peak down in elevation resulted in the patch antenna having about 2 dB less gain than the drooping dipole antenna.

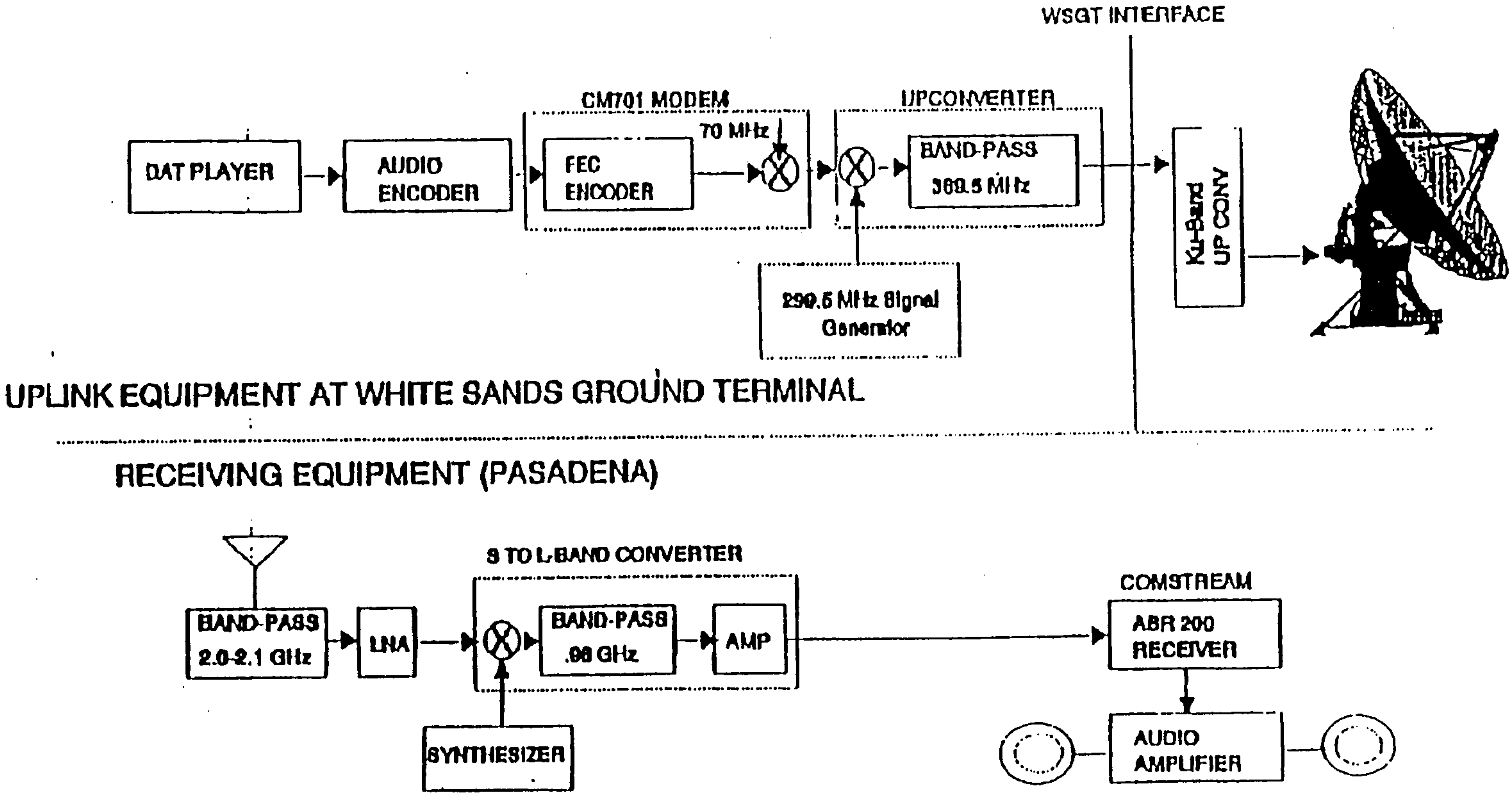
The receiver used was a commercial receiver designed for digital audio distribution to small aperture receive terminals (VSATs) via the fixed-satellite service (FSS). Since it is capable of coherent BPSK demodulation, its performance is close to that of Digital System B in a stationary, line-of-sight reception environment. The receiver provided a readout of the E_b/N_o, which was the most convenient method of checking performance against the link budget.

The performance outdoors, in a line-of-sight environment, was very good. The best readings of E_b/N_o were above 7 dB, which is consistent with the link budget and expected receiver implementation losses. At this signal-to-noise ratio, the bit-error rate is so low that there is no perceptible degradation to the audio quality.

A brief reception test was tried indoors in a room with large windows facing toward the satellite. The windows had metal frames as well as metal grid overhangs for sunshades. Satisfactory reception (E_b/N_o in the range of 5 to 6 dB) occurred in some parts of the room and not in others. The areas of good and poor reception were interspersed and best reception was not necessarily closest to the window. This phenomenon appears consistent with the results of indoor propagation measurements accomplished under the NASA Propagation Program [CCIR Doc. JIWP-WARC-92, § 6], which found a tendency for standing wave structures to form inside buildings.

FIGURE 5

TDRS test and demonstration block diagram



TDRS DIGITAL AUDIO BROADCASTING DEMONSTRATION EQUIPMENT

JUNE 1993

TABLE 15

TDRS test and demonstration link parameters for Pasadena

AUDIO BIT RATE (two-channel stereo)	256.00	kbps
Satellite transmitter power	7.00	watts
Satellite transmitter power	8.45	dBW
Frequency	2.05	GHz
Satellite antenna diameter	5.00	m
Satellite antenna gain	38.02	dBi
Satellite antenna beamwidth	2.05	deg.
e.i.r.p.	46.47	dBW
Satellite elevation angle	20.00	deg.
Slant range	39737	km
Free-space loss	-190.62	dB
Atmospheric losses	0.25	dB
Rain attenuation	0.00	dB
Pointing loss	0.5	dB
Receive antenna gain	4.00	dBi
Received signal	-140.90	dBW
Antenna temperature	150	K
Receiver noise figure	1.50	dB
Receive system noise temperature	274	K
Receive system G/T	-20.37	dB/K
C/N_o	63.33	dBHz
Bit rate	54.08	dB
E_b/N_o available	9.25	dB
Theoretical E_b/N_o, BER = $10E^{-4}$	3.50	dB
Receiver implementation loss	1.50	dB
Interference degradation	0.50	dB
Receiver E_b/N_o requirement	5.50	dB
LINK MARGIN, beam centre	3.75	dB
LINK MARGIN, beam edge	0.75	dB

FIGURE 6A

Drooping dipole antenna

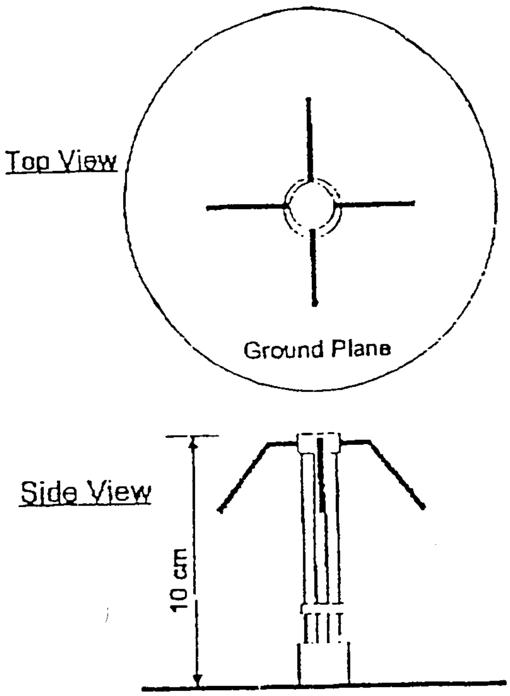


FIGURE 6B

Patch antenna

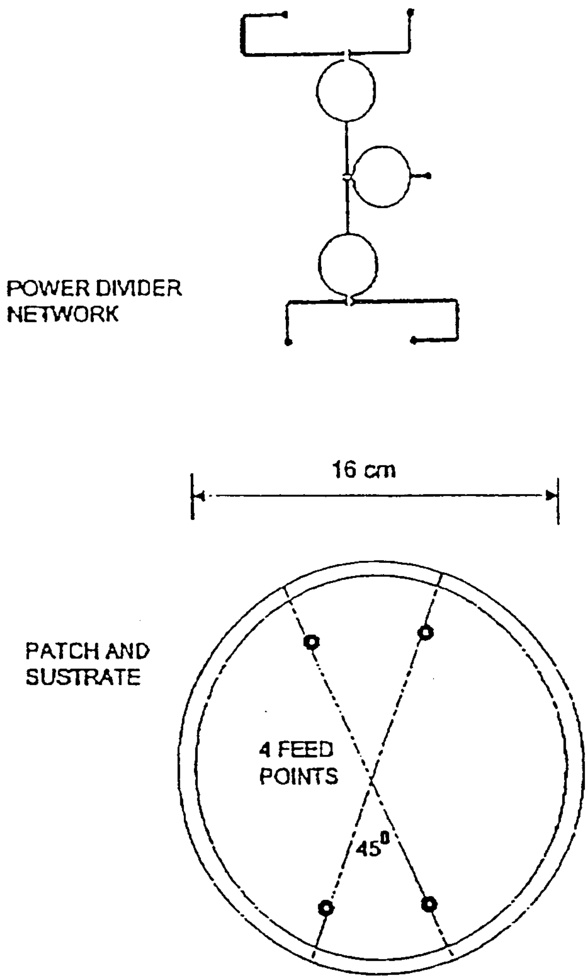


FIGURE 7A

Vertical cut of gain pattern for drooping dipole

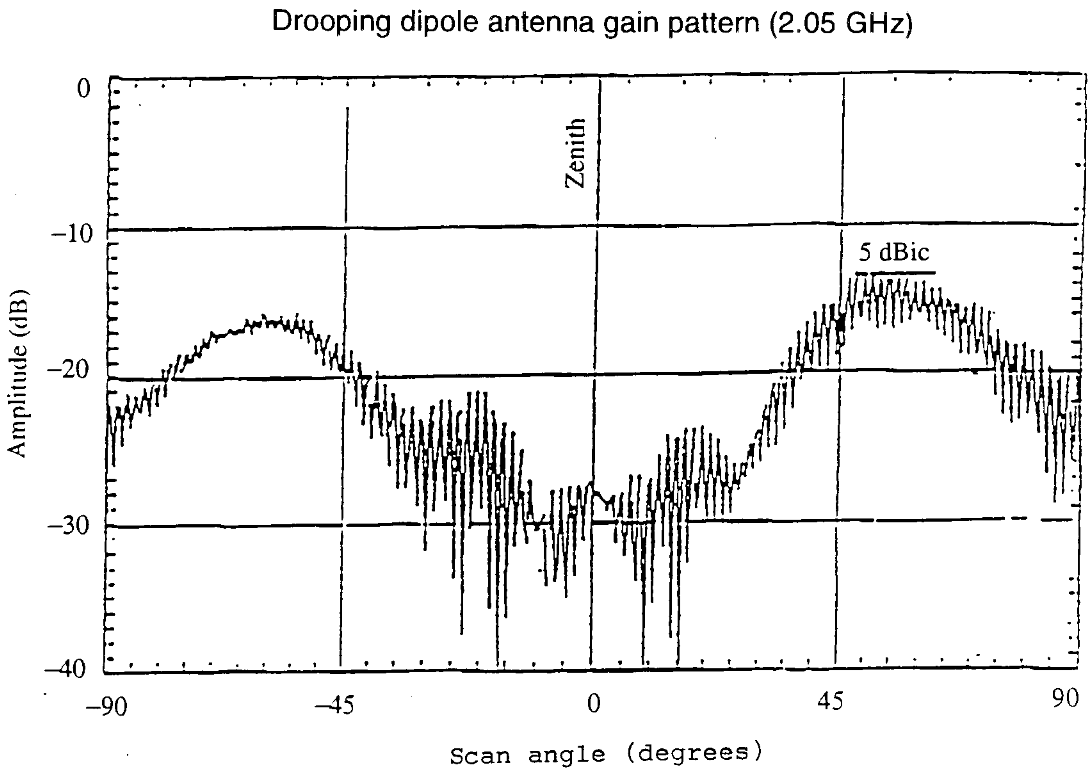
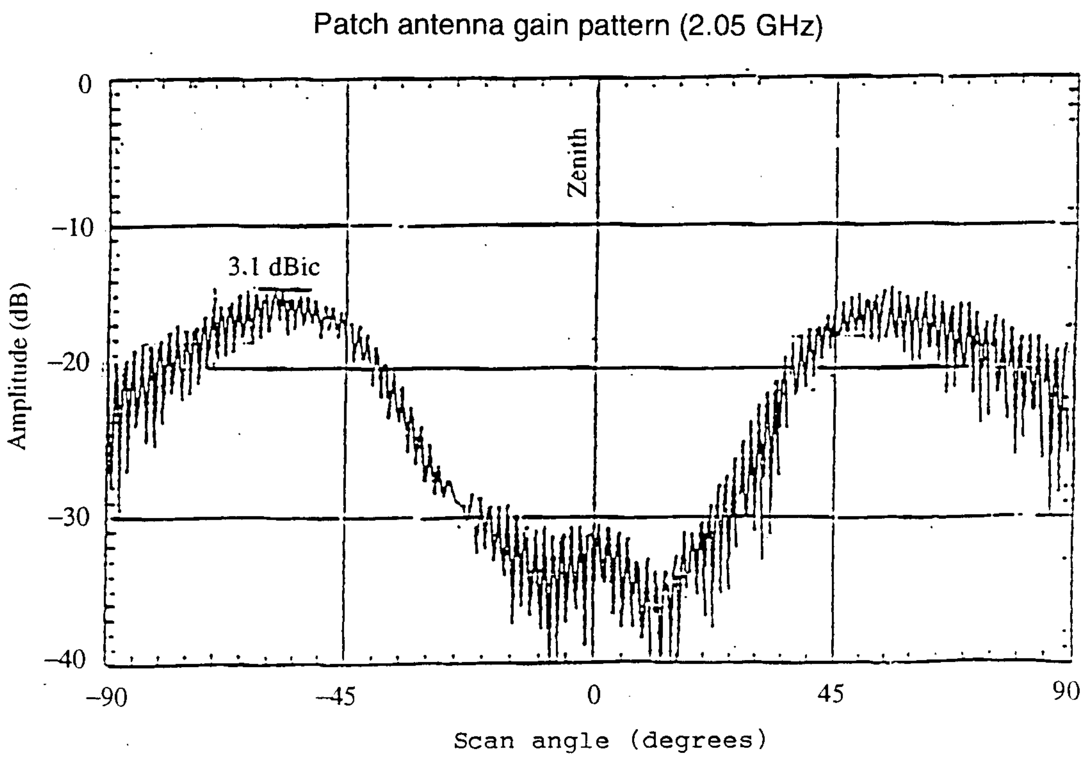


FIGURE 7B

Vertical cut of gain pattern for patch antenna



14.3.3 United States tests and demonstrations in Buenos Aires, Argentina

A test and demonstration of compact disc quality audio similar to that described in § 14.3.1, was conducted in Buenos Aires, Argentina, during the meetings of CITEL PCCII and III in late September 1993. In this case the elevation angle to the TDRS was 50°. Two types of antenna were tried. One was the single-patch antenna operating in the TM_{21} mode, which achieved an azimuthally constant gain of 6 dB at 50° elevation. The second was a 4-patch directional antenna with an on-axis gain of approximately 13 dB. Robust reception was achieved behind a closed window indoors with both antennas.

15. Conclusions

During the past few years, the situation regarding satellite sound broadcasting and complementary terrestrial sound broadcasting has moved rapidly from the domain of studies to experiments and demonstrations of developed prototype hardware using digital techniques for signal processing. These experiments have been conducted both via satellite and via terrestrial measurements. In short, there are no technical and economic impediments to instituting practical sound broadcasting services to vehicular, portable and fixed receivers in a frequency allocation somewhere between 500 and 3 000 MHz.

Various studies, including comprehensive system trade-off studies, indicate that, from a technical and economic standpoint as viewed by broadcasters, carrier frequencies in the vicinity of 1 500 MHz are preferred.

These studies indicate that the initial investment cost for the satellite-based transmission delivery system for a 1° beam is significantly greater at both 750 MHz and 2 400 MHz compared with 1 500 MHz. For a 3° beam the costs at 750 MHz are comparable with those at 1 500 MHz, but the costs at 2 400 MHz remain significantly greater than those at 1 500 MHz.

Furthermore, mixed services that include local, stand-alone terrestrial components become more expensive as carrier frequencies increase. Therefore, on balance, operational frequencies around 1.5 GHz will provide the widest range of implementation flexibility.

As shown in this report, frequencies higher than 1.5 GHz, although more costly, are technically feasible within the range specified by Resolution 520. The non-trivial issue is primarily one of increasing cost for the space segment, the increasing penalty due to Doppler effect with moving vehicles, and the need for a higher density of gap-fillers in those urban areas where these are required as carrier frequencies increase beyond 1.5 GHz.

Estimations of the necessary bandwidth for a frequency allocation have been studied and presented by several organizations. Their conclusions range from 60 MHz to 120 MHz. It has also been shown that the complementary relationship between similar terrestrial and satellite sound broadcasting systems leads to a very efficient use of the spectrum, and is quite feasible.

Since co-located sharing with other services will be difficult, it is preferred that, at any location on the Earth, the frequencies used for BSS (Sound), including complementary terrestrial broadcasting, will not be used by other services. This does not preclude geographic sharing within a regional or worldwide allocation. Digital modulation enhances the attractiveness of geographic sharing by minimizing the geographic separation distances needed.

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ANNEX 1

Satellite transmitting antenna technology

[CCIR, 1986-90a Doc. 10-11S/53 (United States)]

1. Introduction

With the relatively lower e.i.r.p. now required (see § 6.4 of the present Report) which will result in a lowering of the required primary power and thus the total satellite size, it seems that the satellite antenna remains the only critical element in the realization of the space segment to provide UHF sound BSS. This Annex covers the details of a number of techniques to realize the antennas and their expected performance.

Satellite-borne antennas with diameters in the range of 5-55 m are currently in various stages of development for advanced applications such as mobile communications satellites, orbiting very-long-baseline-interferometry (VLBI) astrophysics missions, and Earth remote sensing missions [Freeland *et al.*, 1986]. The technology being developed for these other types of applications is directly applicable to satellite sound broadcasting systems operating in band 9.

Satellite-borne antennas with diameters greater than about 3-4 m must be designed so that they may be launched in a stowed configuration, and deployed once the satellite has achieved its proper orbit and has been stabilized. This constraint has led to large-aperture, reflector antenna designs based on the use of a collapsible or foldable support structure and of a light-weight, pliable, metallized mesh reflector surface.

The types of supporting structures used on the different satellite-borne antennas currently under development include the hoop/column, the tetrahedral truss, and the wrap-rib. Figure 12 shows the wrap-rib and hoop/column antennas both in the partially deployed and fully deployed stages. These deployable antennas are all of relatively lightweight and use a mesh material as the reflecting surface. In the deployed configuration, the mesh antenna surface is formed into a paraboloid either by a series of tie-points between the members of the supporting structure and the mesh (the hoop/column and tetrahedral truss antenna) or by attaching the mesh to a shaped rib (the wrap-rib antenna). The surface accuracies achieved using these shaping techniques are such that the measured radiation patterns of these developmental antennas generally conform to the co-polar reference pattern for satellite transmitting antennas given in Fig. 3 of Recommendation ITU-R BO.652.

A summary of deployable satellite antennas is given in Table 4 of the present Report.

2. Supporting structure

2.1 Hoop/column

A 15 m diameter hoop/column antenna has been built and tested in a ground environment [Belvin and Edighoffer, 1986]. The antenna deploys from a volume of about 1 m in diameter by 3 m high to a structure that is 15 m in diameter by 9.5 m in height. A motor driven cable system is used to deploy the antenna.

2.2 Tetrahedral truss

A technology-demonstration 5 metre diameter tetrahedral truss antenna has been built and tested [Dyer and Dudeck, 1986]. When packaged, the overall antenna height is 1.8 metres, the truss height is 1.1 metres, the mesh diameter is 1.4 metres, and the truss diameter is 0.9 metres. The antenna is a freely deploying system that does not require motors to deploy. Deployment makes use of energy stored in the folded spring hinges (carpenter tape hinges) of the structure.

2.3 Wrap-rib

Large-aperture, deployable reflector antennas based on the wrap-rib design use the most mature deployable antenna technology available [Naderi, 1982]. A 9.1 metre diameter version of this antenna was flown on the Applications Technology Satellite-6 (ATS-6) in 1974 [Marsten, 1975]. A preliminary design study was conducted in 1979 to characterize offset fed and axi-symmetric reflector antennas for missions requiring antennas in the 100 metre of 150 metre diameter range. The study identified critical technologies, estimated the cost and schedule required to develop the antenna, and developed a technology plan for a low-cost, low-risk "proof-of-concept" demonstration [Freeland et al., 1984].

The proof-of-concept was demonstrated in 1984, when a partial reflector was deployed in a simulated zero-gravity environment. The proof-of-concept model was a segment of a 55 metre diameter reflector consisting of a central hub (around which the ribs are wound when in the stowed configuration) and four ribs (contoured to the shape of a parabola) to which the mesh reflector material was attached. The tests demonstrated the efficiency of the deployment method and of the mesh-development management system.

3. Reflector surface

The performance of these large aperture space-borne antennas may be affected by the characteristics of the reflector material and by the accuracy of the reflector contour.

3.1 Effects of the wire mesh

A knitted wire mesh is the reflector material of choice for each of the antenna types cited. A typical mesh is a tricot knit of 0.003 cm diameter gold-plated molybdenum wire with about three openings per centimetre. An analysis to determine the effects of the knitted wire mesh of the gain, side lobe, and cross-polarization performance of large-aperture antennas has been performed [Rahmat-Samii and Lee, 1985]. It was shown that the performance of the mesh reflector antenna should be comparable to that of a solid reflector antenna when the geometry of the mesh material was properly selected (i.e. by properly selecting the opening size relative to a wavelength, rectangular vs. square openings, and the orientation of the rectangular opening relative to the incident polarization vector). Specifically, side lobes in excess of 30 to 35 dB below the level of the main beam were achievable using a pliable, light-weight, wire mesh reflector material.

3.2 Surface accuracy

The hoop/column and the tetrahedral truss antennas use tie-points to connect the mesh surface to the support structure and to form the surface into a parabolic shape. It was found that grating lobes were generated in the far-field pattern by periodic "pillowing" of the surface, which was in turn, caused by errors in "tensioning" the uniformly spaced tie-points. When the placement of the tie-points was randomized, the grating lobes were no longer evident [Bailey, 1986]. Fig. 13 illustrates the measured performance of an offset-fed, 5 metre tetrahedral truss antenna operating at a scale frequency of 4.26 GHz [Dyer and Dudeck, 1986]. It is noted, that this performance should scale to a 20 metre diameter antenna operating at a frequency around 1 GHz.

The achievable surface accuracy of the wrap-rib antenna has also been studied. This antenna design relies on both the accuracy and on the thermal characteristics of the rib cross-section to define the reflector surface formed by the mesh. Studies of the performance of a 20 metre diameter wrap-rib antenna in a space environment indicate that an r.m.s. surface accuracy of 3 mm can be achieved [Freeland, 1987]. This corresponds, for example, to an r.m.s. surface accuracy of $\lambda/100$ at an operating frequency of 1 GHz; a value that will ensure low side lobes.

4. In-orbit tests

In order to verify that these large aperture deployable antennas will perform as required in a space environment, it is necessary to test them in an environment that simulates, as closely as possible, the zero-gravity and thermal vacuum conditions found in outer space. Ground testing of these antennas, even when suitable facilities exist, is extremely difficult and expensive, and frequently yields results of questionable value. A flight test of a high-performance, low-side lobe, 20 metre diameter wrap-rib prototype antenna system on the Shuttle or an another suitable vehicle is being studied as a means to significantly reduce the risk and uncertainty associated with the operational use of an antenna and to provide the added benefit of helping to validate ground test procedures for future antenna systems [Freeland et al., 1986; Freeland, 1987].

5. Reference antenna patterns for the broadcasting-satellite service (sound)

5.1 Technical considerations

The desired satellite antenna pattern for the space-to-Earth transmission path should provide a footprint as closely shaped to the geographical service area as possible and with as rapid as possible gain roll-off beyond this area. Such patterns have been achieved in the 11.7 - 12.7 GHz frequency range by parabolic reflectors with multiple feeds creating shaped beams (see IEEE Transactions on Antennas and Propagation, Vol. 41, No. 6, June 1993, pp. 713-722). More recently, it has been shown that the desired pattern can also be achieved using a shaped reflector with a single feed [ITU, October 1993, Doc. 10-11S/157 (United States)].

The results of initial technical consideration indicate that, theoretically, antenna beam shaping can be achieved in the 1.4 - 2.6 GHz frequency range with performance equivalent to that achieved in the 11.7 - 12.7 GHz frequency range. If this can be accomplished in practice, it would be possible to adopt the reference patterns for satellite transmitting antennas given in Figs. 3, 4, and 5 of Recommendation 652-1. These patterns, which are based on Figs. 9, 10, and 11 of Appendix 30 (Orb-85), Annex 5, are attached for convenience as Figs. 8-10. It may also be possible to adopt one of these patterns for all Regions depending on future detailed studies.

5.2 Current uncertainties

It is very important to note that the antenna gain roll-off patterns shown in Figs. 8-10 may not be attainable in practice either for the co-polar or the crossed polar components. The reason for the uncertainty stems from the large physical dimensions of both the satellite aperture and the feeds and feed supports in the 1.4 - 2.6 GHz frequency range as compared to the 11.7 - 12.7 GHz frequency range. To be more specific, a 2° beamwidth (3 dB) at 12 GHz requires a satellite antenna reflector only 0.93 m (2.8 ft) in diameter, whereas at 2 GHz the satellite antenna reflector diameter is 5.6 m (16.8 ft). For a multi-feed antenna, the size of the feed structure is of particular concern since it can be very large depending on the antenna system's f/D ratio:

1) Multiple feeds would prove difficult since the large size of the feeds requires physical displacement from the true paraboloidal focus. The resultant defocusing causes increased antenna side lobes as well as on-axis gain loss.

2) The blockage caused by symmetric multiple feeds would contribute to increase antenna side lobes and back lobes as is shown in the attached Fig. 11.

3) Mutual coupling between the feeds, diffraction and scattering from the feeds and feed supports and undesired radiation modes would contribute to increased antenna side lobes and back lobes.

Another uncertainty is whether shaping of the antenna reflector is feasible for an antenna of such a large size, thereby allowing shaped beams with a single feed horn arrangement.

5.3 Conclusion

It is believed that one approach to achieving satellite transmitting antenna gain roll-off patterns in the 1.4-2.6 GHz frequency range comparable to those achieved in the 11.7-12.7 GHz frequency range is to use a shaped parabolic reflector with a single offset feed. Experimentation during 1994 should provide data on which to assess whether satellite transmitting antennas in the 1.4-2.6 GHz frequency range can yield patterns with envelopes that comply with the reference patterns given in Recommendation ITU-R BO.652.

6. Summary and conclusions

There is significant work underway to develop high-performance, deployable, light-weight, space-qualified reflector antennas with diameters ranging from 5 m to over 55 m and which exhibit side lobe levels on the order of 30 dB or more below the peak gain of the antenna. Axi-symmetric and offset-fed antennas are being developed. A tricot knit, gold-plated molybdenum wire mesh is used for the reflecting surface. Analyses, confirmed by experiment, show that a properly chosen wire mesh reflector surface will not degrade the antenna performance in the side lobe region. When this condition is met, the antenna performance in the side lobe region is primarily determined by the mechanical deviations of the reflector surface from a paraboloied. During the course of developing the tetrahedral truss antenna, it was found that random positioning of the tie-point locations was an effective means by which to eliminate the grating lobes exhibited by antennas that use regularly spaced tie-points.

The difficulties associated with space-qualifying these large-aperture deployable antenna structures using ground testing has led to the study of using flights of the Shuttle or other suitable vehicles to perform the requisite qualification tests. In-orbit testing of a high-performance, 20 m diameter wrap-rib antenna is being studied.

It may be concluded on the basis of the on-going work cited in this contribution that the satellite transmitting antenna radiation pattern given in Fig. 9 of Annex 5 to Appendix 30 (ORB-85) is a viable reference radiation pattern to use for sharing studies and for system studies involving satellite sound broadcasting systems operating in band 9.

FIGURE 8

Reference patterns for co-polar and cross-polar components for satellite transmitting antennas in Regions 1 and 3

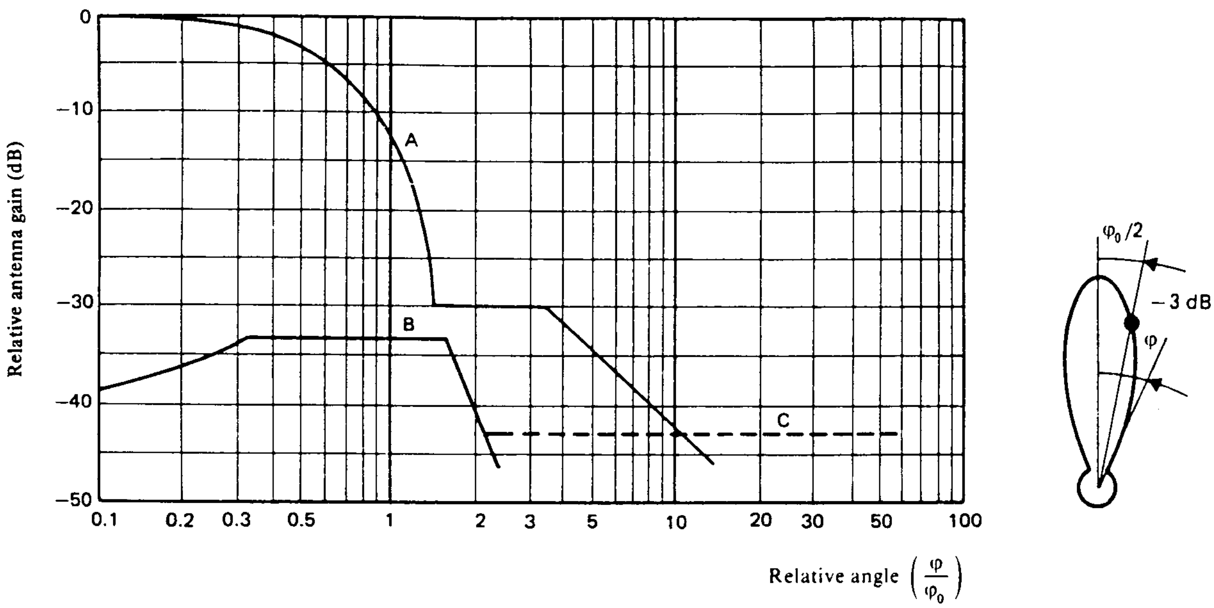


FIGURE 9

Reference patterns for co-polar and cross-polar components for satellite transmitting antennas in Region 2

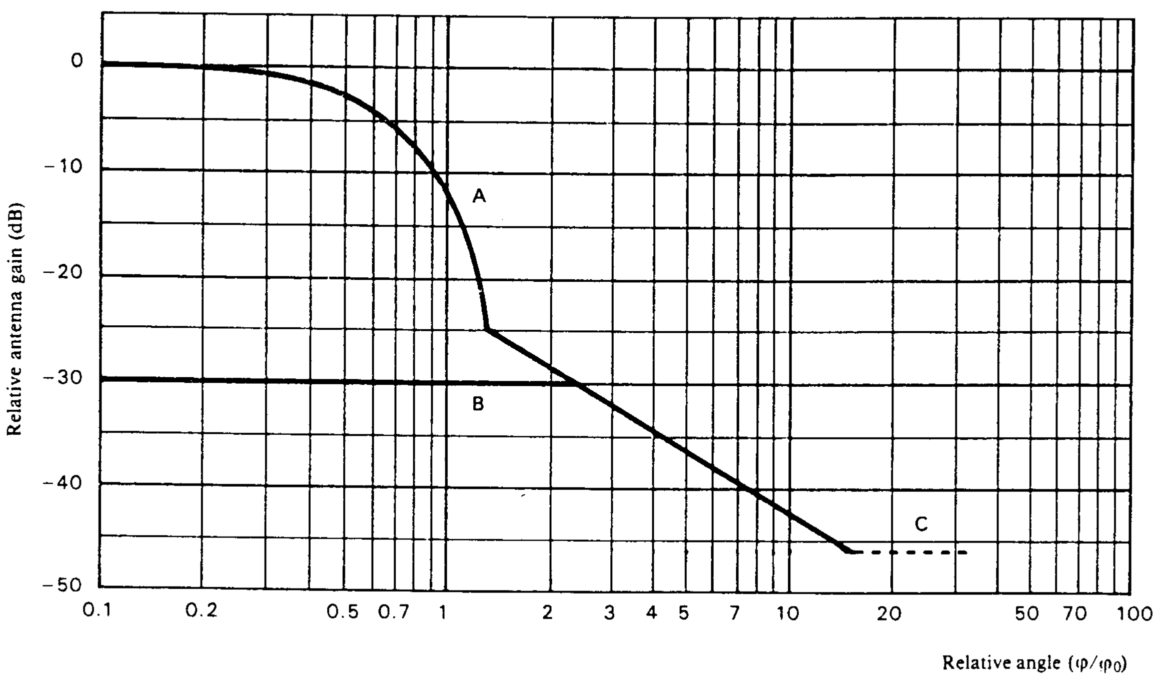


FIGURE 10

Reference patterns for co-polar and cross-polar components for satellite transmitting antennas with fast roll-off in the main beam for Region 2

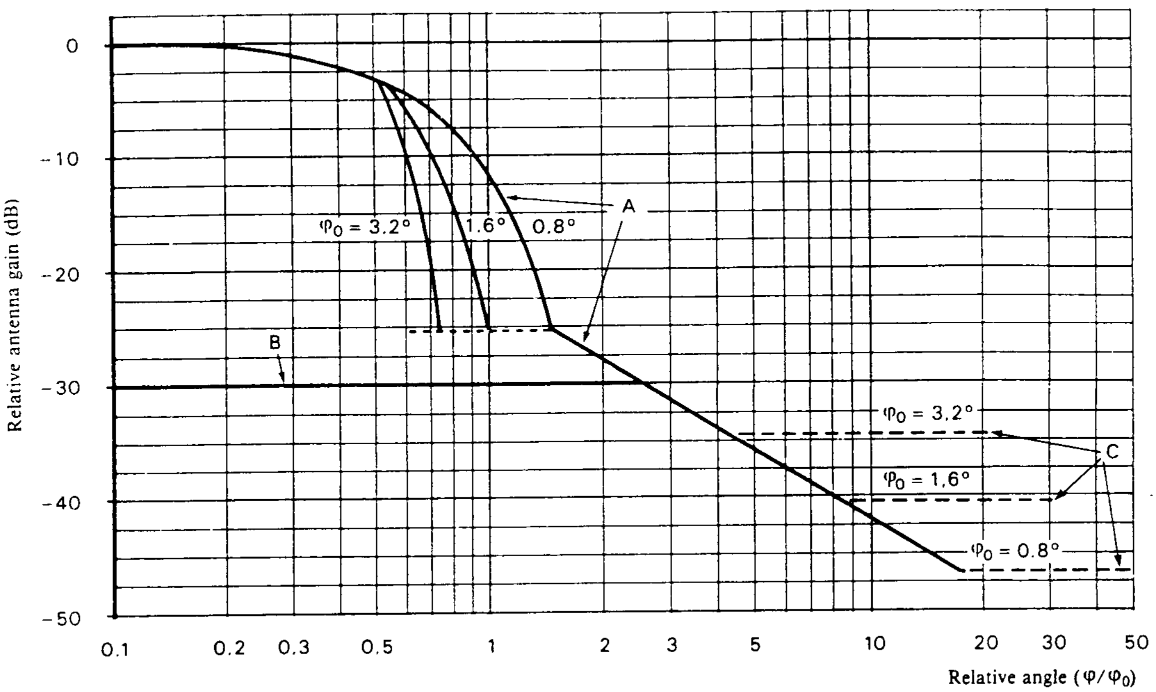


FIGURE 11

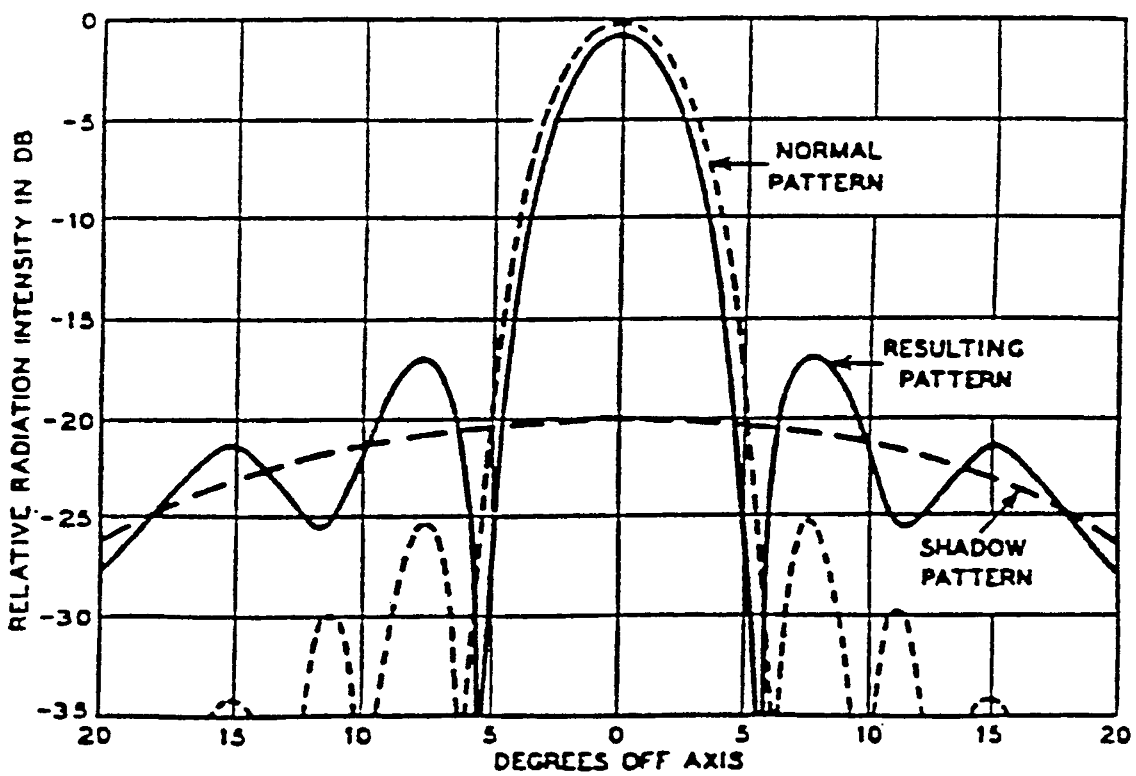


FIGURE 12

Partially- and fully-deployed wrap-rib and hoop/column antennas [Jordan et al., 1984]

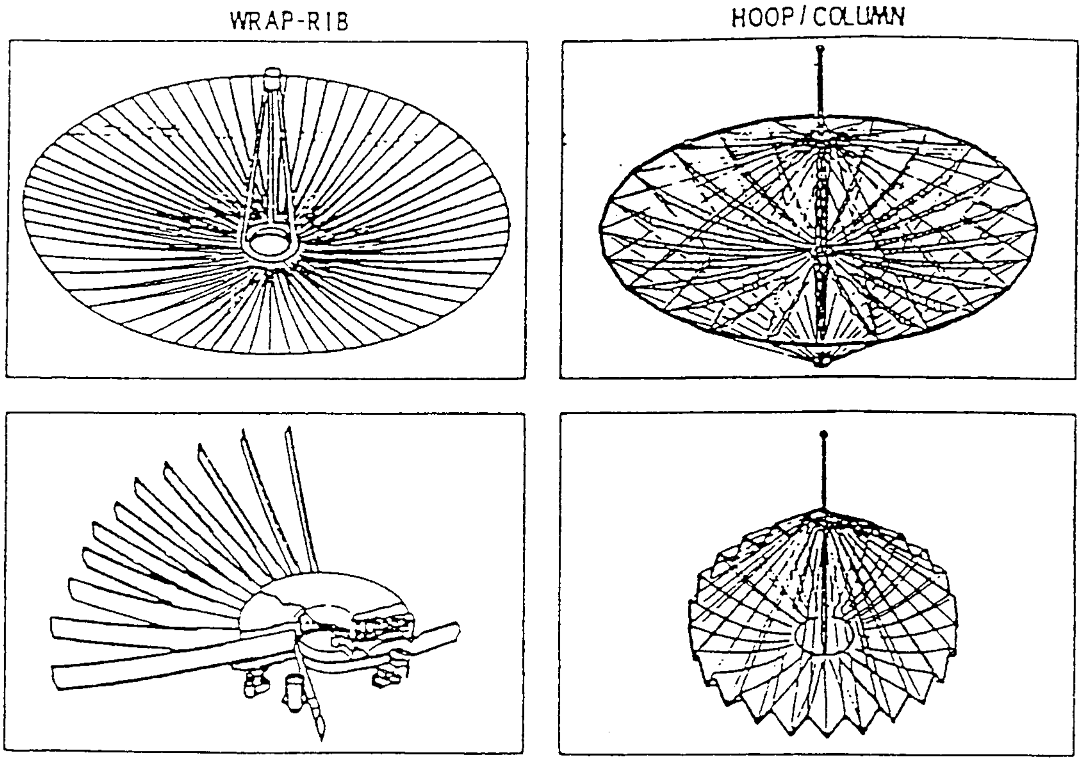
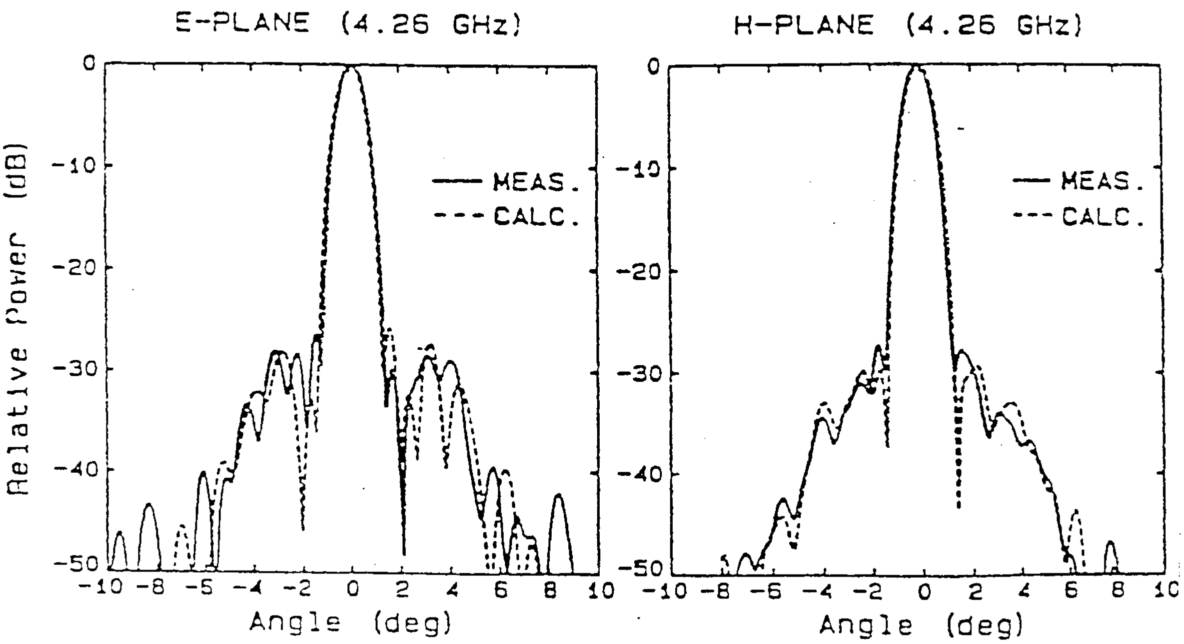


FIGURE 13

Comparison of the calculated and measured antenna pattern of a 5 metre tetrahedral truss antenna operating at 4.26 GHz [Bailey, 1986]



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ANNEX 2

Propagation characteristics and link margins of the UHF satellite channel

[CCIR, 1978-82, Docs. 10-11S/143 (USA), 10-11S/176 (ESA) and 10-11S/177 (ESA)]
[CCIR, 1986-90, Doc. 10-11S/1 (EBU)]

1. Introduction

Satellite sound broadcasting to portable and mobile receivers is different in several respects from its terrestrial counterpart. On the other hand, there are some similarities with satellite land-mobile communications.

Previous studies by the EBU [CCIR, 1978-82, Doc. 10-11S/10 (EBU)] and the United States [CCIR, 1978-82, Doc. 10-11S/29 (USA)] considered specific examples of link budgets and link margins for certain angles of elevation, conditions of reception and other parameters. Two specific methods have been suggested and various aspects are analysed and compared in section 3 of this annex.

The recent experiments have shown substantial agreement with the signal power distribution functions for large and small areas (see section 2). In the light of the European experimental programme [Jongejans, 1986], a new composite propagation model is proposed. This model combines both the small area Rice/Rayleigh probability function and the large area log-normal probability distribution.

The design of suitable modulation systems for the type of broadcasting service will rely on propagation statistics relating to time-delay spread and correlation bandwidth of the transmission channel. These concepts, together with other related topics are presented in section 4 of this annex, together with the experimental data.

2. Propagation models

The probability distribution functions relevant to the reception of satellite signals were found to correspond to a number of statistical distribution models related to the specific environment. These distribution models are generally different in so-called "small areas" and "large areas". The former are usually defined as locations extending over a number of wavelengths (for example over 40 wavelengths resulting in a distance of about 10 m). The latter extend over several small areas.

2.1 Large area distribution function

On large areas, it has been found experimentally [Guilbeau, 1979; Hess, 1980; Lutz, 1986; Jongejans 1986], that the probability distribution function of the mean received signal power takes the log-normal form:

$$p_{LN}(S_o; \mu, \sigma) = (K/(S_o\,\sigma)) \exp\left[\left(-1/2\right)\left((L_{So} - \mu)/\sigma\right)^2\right] \qquad (1)$$

$$K = 10/(\sqrt{2\pi}\ln 10)$$

where:

$\underline{S}o(W)$: mean received signal power over a small area;
$\overline{S}f(W)$: mean received signal power over a large area under free space propagation conditions;
$L_{So}(dB)$ = 10 log $(So/\overline{S}f$ level of So relative to free space level;

$\mu(dB)$ = mean of L_{So} over a large area;

$\sigma(dB)$ = standard deviation of L_{So} over a large area.

In equation (1), the mean value and the standard deviation are both expressed in terms of dB, relative to the free-field power level, in order to facilitate comparison between the theoretical model and measured data.

The large area model given above was experimentally verified and confirmed by [Lutz et al., 1986] and [Jongejans et al., 1986]. Using the same notation as in equation (1), the following parameter values were measured (see Table 16).

TABLE 16

Measured large area parameters for various environments

Environment	Antenna	$\mu_{sh}(dB)$	$\sigma_{sh}(dB)$	CF	$\mu_{los}(dB)$	$(C/M)_{los}(dB)$
Urban	C3 D5 S6	-10.7 -12.2 -12.9	3.0 4.4 5.0	0.60 0.78 0.79	-1.8 -4.9 -5.2	3.0 9.3 11.9
Woods	C3 D5 S6	-9.3 -5.3 -5.8	2.8 1.3 1.1	0.59 0.54 0.56	-2.7 -1.8 -2.1	9.9 10.7 12.9
Highway	C3 S6	-7.7 -7.0	6.0 4.8	0.25 0.23	-0.4 -0.6	11.9 18.3

where:

$\mu_{sh}(dB)$: μ in shadowed areas,

$\mu_{los}(dB)$: μ in non-shadowed (line-of-sight) areas,

$\sigma_{sh}(dB)$: standard deviation of S_o in shadowed areas,

CF: clutter factor, defined as the proportion of the time for the direct path being obstructed assuming a constant vehicle speed,

$(C/M)_{los}(dB)$: ratio of direct (carrier) signal to the diffuse multipath power in non-shadowed (line-of-sight) areas,

C3: hemispherical pattern, 3 dBi gain,

D5: toroidal pattern, 5 dBi gain,

S6: toroidal pattern, 6 dBi gain.

Several points may be deduced from Table 16:

- The measured average power levels in shadowed areas are very much less than those in non-shadowed areas in the same environments; for example, in urban zones the additional attenuation due to shadowing may be as high as 9 dB, in the woods 6.5 dB and on highways 7 dB. It follows that the main problem in providing a service is to overcome shadowing effects.
- The influence of the type of the receiving antenna seems to be quite significant especially on the ratio between the direct component and the multipath power in the non-shadowed areas.
- In urban areas, the shadowing loss is proportional to the antenna gain. Standard deviation, σ, and C/M (see § 2.2 of the present annex) ratio are proportional to the antenna gain. This last fact may be significant in the design of digital modulation systems for reception in urban areas.

In the European experiment simulation of the satellite transmission conditions were created by positioning the transmitting antenna on the Eiffel tower in Paris and measurements were made at a frequency of 839 MHz and for an average elevation angle of 25° [Guilbeau, 1979]. From this reference one can extract the parameters for equation (1). Table 17 lists these parameters together with the values predicted from United States' data for the frequency of 839 MHz and an elevation angle of 25°. The values of the PROSAT experiment are derived from Table 1.

TABLE 17

Urban zone					
Parameters of log-normal distribution for urban areas			Average	Obstructed visibility	Direct visibility
μ	(dB)	Guilbeau	-7.5	-11.5	-0.7
		(USA)	-6.3	-10.1	-2.6
		PROSAT	-6.3	-10.7	-1.8
σ	(dB)	Guilbeau	3.2	2.9	2.0
		(USA)	3.7	4.3	3.1
		PROSAT	-	3.0	-

From this table it can be seen that reasonable agreement exists between the three experiments.

Measurements made with the ATS-6 satellite in the United States [Hess, 1980] provide values for μ and σ for different areas under different receiving conditions. From the above reference a simple method for the assessment of μ and σ can be derived as follows:

$$\mu = - [A + 1.93 f - 0.052 \delta] \quad (2)$$

$$\sigma = 1/2 [B + 0.053 f + 0.040 \delta] \quad (3)$$

where the parameters μ, σ, $\overline{S}o$ and $\overline{S}f$ are defined in equation (1), and

f: frequency (GHz)

σ: elevation angle (degrees).

Values for A and B are given in Table 18 for different receiving conditions. In the table direct visibility indicates instances where the streets in the urban area are running parallel to the satellite azimuth and obstructed visibility is on streets running perpendicular to the satellite azimuth combined with the unfavourable side of the street.

TABLE 18

	Urban zone			Suburban/rural zone		
	Average	Obstructed visibility	Direct visibility	Average	Obstructed visibility	Direct visibility
A (dB)	6.0	9.8	2.3	1.1	5.1	0.5
B (dB)	6.4	7.6	5.2	1.1	2.4	-

These values were partially derived from [Hess, 1980] by extrapolating with the assumption that sensitivities were 0.1 dB/percent for rural and 0.2 dB/percent for urban areas, below the specified 90% coverage level. They were confirmed by the European experiments [Lutz and Jongejans, 1986] for urban areas and woods. However, this modelling does not seem to be appropriate for the non-shadowed highways.

2.2 Small area distribution functions

The recent European [Jongejans, 1986] and United States' data indicate that the small area behaviour of the received signal can be modelled by a Rician distribution (constant vector plus Rayleigh distributed vectors).

If the ratio of direct signal power C to the diffuse multipath signal power M is denoted as C/M, the envelope probability distribution in an isolated small area is given by equation (4):

$$p(r) = (r/M)\ (\exp(-r^2/2M - C/M) \cdot I_o\,[r\sqrt{2C/M}] \qquad (4)$$

The parameter C/M is important as a measure of fading characteristics* of the channel. If C/M is high, the envelope probability distribution p(r) approaches a Gaussian distribution with mean $\sqrt{2C}$ and standard deviation $\sqrt{M}$. If C/M is low, p(r) approaches a Rayleigh distribution since: the modified Bessel function of first kind zero order approaches 1 as z approaches 0.

* The time intervals with received power level below a certain threshold are called fades.

The corresponding probability density of $y = \frac{r^2}{\bar{r}^2}$ is given by:

$$P_R(y) = (C/M + 1) \exp [-y(C/M + 1) - C/M] \cdot I_o [2\sqrt{y(1 + C/M)C/M}] \tag{5}$$

where:

$$y = r^2/\bar{r}^2 = r^2/s_o$$

The level crossing rate (LCR) at the level V is given by equation (6):

$$LCR = \frac{b}{\sqrt{2\pi}} P_R (V) \tag{6}$$

where P_R (V) is the envelope of the Rice probability density function at the value V, and b is the function of magnitude and the frequency content of the multipath reflections:

$b = 2 \pi^2 B_d^2 M$, where B_d is a Doppler spread.

Equation (6) shows that the level crossing rate and probability density function are closely linked. Therefore, the parameter C/M of P_R (y) can be determined through the measurement of LCR.

The average fade duration (AFD) at the level V is given by:

$$AFD = (1/LCR) \int_o^V P_R (r)\, dr \tag{7}$$

AFD is an important factor in designing a digital transmission system which should be designed in such a way that it overcomes long fades using a complex interleaving system.

The validity of the Rice model has been demonstrated by the PROSAT experiment on the basis of a composite log-normal - Rice mode (see § 2.3 of the present annex).

Some typical average values of C/M for non-obstructed visibility are given in Table 16 (see § 2.1 of the present annex). Since C/M is the only parameter used in $P_R(y)$ given by equation (5), the Rice probability function $P_R(y)$ is fully characterized if C/M is known.

In [Jongejans, 1986] some typical values of LRC and AFD at mean envelope level are given for vehicle speed 30 km/h. They are reproduced in Table 19 below:

TABLE 19

The LCR and AFD values in different environments

	LCR (Hz)	AFD (ms)
Open area	30	20
Suburban	14	40
Rural	16	33

2.3 The combined propagation model

European researches [Jongejans, et al., 1986] and [Lutz, 1986] concluded that the probability density function of the received power should combine log-normal and Rice (Rayleigh) distribution in order to take account of both large-area variations and small-area variations. The distribution of instantaneous values in a small area is obtained by considering a Rice or Rayleigh variable whose mean value is itself a random variable having a log-normal distribution. The combined distribution of the received power S may be described as shown in equation (8):

$$P(S) = CF \int_0^{S_m} P_r(S,So)\ P_{LN}(So)\ dS_o + (1 - CF) \int_{S_0}^{S_m} P_R(S,So)\ P_{LN}(So)\ dS_o \qquad (8)$$

where:

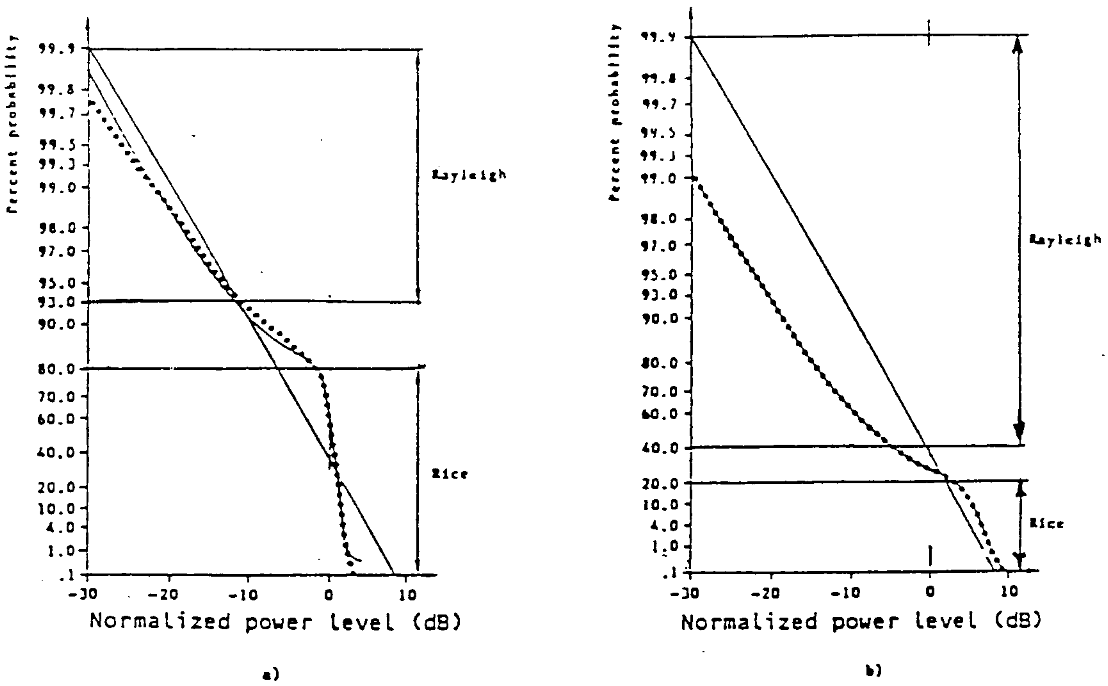
- S_o: average received signal power over small area (S_o = C + M)
- p(s): combined distribution density function of the instantaneous received power in a small area
- P_r(S,So): Rayleigh distribution over obstructed (shadowed) small areas
- P_{LN}(So): distribution of mean power of small areas distributed over a large area
- Sm: maximum obstructed power over a large area concerned
- P_R(S,So): Rice distribution over non-obstructed (non-shadowed) small areas
- S_M: maximum line-of-sight power over a large area concerned
- CF: clutter factor, defined as the proportion of the time for the direct path being obstructed assuming a constant vehicle speed.

Figs. 14a) and 14b) show complementary cumulative probability distribution functions of the normalized received power on highway and in city environments [Lutz et al., 1986]. The two figures are plotted on a Rayleigh scale. The full lines represent the theoretical channel model. Statistics of the recorded channel obtained by the measurements are designated as dots.

Three parts of the curves can be distinguished. At low values of the received power, the curve slope approximates the slope of the straight diagonal line which corresponds to a Rayleigh distribution; thus this part of the curve has clearly Rayleigh characteristics. At high values of received power, the slope of the curve indicates a Rice distribution; on highways, the Rice law is followed in 80% of small areas whereas in city environments it applies in 20% of small areas. The central part of the curves follows a log-normal law.

Similar results have been obtained [Jongejans et al., 1986]. They all demonstrate very good compliance between the theoretical models and the measuring results.

FIGURE 14
Complementary cumulative probability distribution function of received power [Lutz, 1986]



a: Highway, antenna S6

b: City, antenna S6

2.4 Suitability of the propagation model for COFDM

2.4.1 Narrow-band signals

The previous sections give a propagation model based on the measurement data available from narrow-band signals [Hess, 1980].

According to this propagation model, the received power is distributed in the so-called large areas, each of them being subdivided into a number of the so-called small areas. If P_r is the mean power received in a small area, then 10 log P_r follows a normal (Gaussian) distribution law. Within small areas, the received power P_r follows a Rice-Nakagami distribution law. The mean value of this distribution is P_r. If there is no direct path, the Rice-Nakagami distribution becomes a Rayleigh distribution.

The received power P_r is statistically distributed in accordance with the joint probability law (i.e. the Rice-Nakagami conditioned by the log-normal law).

Considering a small area, since the COFDM system is well matched to the propagation channel, then the majority of multipath signals will lie within the system guard interval. In this case, the received power equals the power sum of all signals received, either direct or reflected, regardless of their relative phase. Because the phase relationships can now be disregarded, it follows that the Rayleigh (or Rice-Nakagami) distribution laws for small areas can be dispensed with.

In a large area which consists of a number of small areas, the received power distribution will follow a log-normal law. Therefore, in the case of COFDM, the log-normal distribution should be applied to the calculation of the link margin.

2.4.2 Wideband signals

In September 1993, in order to improve the propagation and coverage field prediction in urban and rural areas, for terrestrial digital audio-broadcasting, numerous wideband field strength measurements were performed by CCETT from a single transmitter antenna situated on the France Telecom transmission tower at Rennes in France. This experiment was realized in the 1 500 MHz frequency range with third generation Digital System A prototype equipment. The conclusions were the following:

1. The ITU-R model used over a large sector (300 m interval) is verified according to normal logarithmic law with the following values:

   $\sigma = 5.1$ dB

   location variation margin 50% to 99% ≈ 11.3 dB.

2. The Rice-Nagakami model used over small sectors (50 m interval) does not seem to comply with the probabilities obtained. There is a discrepancy in the good sense of the term, because a significant reduction of about 99% may be observed in relation to the theoretical Rayleigh Curve (-20 dB). The distribution tends to follow a normal logarithmic law with the following values:

   $\sigma = 4.7$ dB

   location variation margin 50% to 99% ≈ 10.6 dB.

3. Link margins

For a satellite sound-broadcasting system, the link margins must be carefully specified - they should be neither optimistic nor pessimistic. An optimistic estimate will result in the service quality objective not being met, whereas a pessimistic estimate will needlessly result in the over-design of the satellite. Both of these extremes have substantial cost implications.

Two specific methods for the calculation of the required margins needed to provide a given quality of service are indicated below:

3.1 Method 1

Method 1 requires that in a small area the received signal envelope must be above the receiver threshold with probability 0.9:

$$P(r \geq R_0) = 0.9 = \int_{R_0}^{\infty} p(r)\, dr \tag{9}$$

where

R_0 is the receiver threshold and $p(r)$ is given by equation (4).

It is also required that this condition be met over a larger area with probability 0.9. Invoking the large area probability distribution given in equation (1):

$$P(S_0 \geq \hat{S}_0) = 0{,}9 = \int_{\hat{S}_0} p(S_0)\,dS_0 \tag{10}$$

where $\hat{S}_0 = \frac{E_0^2}{2} + \sigma_r^2$, which satisfies equation (9).

Equation (9), conditioned by equation (10) can be solved numerically using Marcum's Q functions [Brennan and Reed, 1965] or by using the tables supplied by [Norton et al., 1955]. Both methods were used in calculation as a cross check on each other. Equations (9) and (10) were solved to satisfy the given probabilities in terms of $G = \mu + 10 \log (2\,\overline{S}f / R_0^2)$ which is the difference between the large area mean received power and the receiver threshold. Total link margin is given by $L = G - \mu$ (in dB).

Table 20 shows the results of the above calculation for the frequency of 1 GHz and an elevation of 30°.

TABLE 20

	Urban zone	Rural zone
σ (dB)	3.8	1.2
μ (dB)	-6.4	-1.5
G (dB)	15.4	6.1
L (dB)	21.8	7.6

It should be noted that the values used for σ and μ are average values and are not those applicable to the obstructed visibility case.

The calculated margin of 21.8 dB for the urban area compares with the observed margin of 24.2 dB (translated to 1 GHz) in urban Denver of the United States [Hess, 1980].

It is pointed out that the computed margin depends on the required service quality and coverage. In this example it was assumed that the required service quality was achieved when the signal was above threshold with probability 0.90, and that this condition was to be met with probability 0.90 over the coverage area. Other requirements will lead to different margins.

3.2 Method 2

Method 2 requires that the received signal envelope in a given area must be above the receiver threshold (R_0) with probability 0.9. This leads to:

$$P(r \geq R_0) = 0.9 = \int_0^{\infty}\int_{R_0}^{\infty} p(r)p(S_0)\,dr\,dS_0 \tag{11}$$

This integral is evaluated numerically using Marcum's Q functions in steps of $G = 10 \log_{10} (2 \overline{So} / R_o^2)$.

Results are shown in Table 21, again for the frequency of 1 GHz and elevation angle of 30°.

TABLE 21

	Urban zone	Rural zone
σ (dB)	3.8	1.2
μ (dB)	-6.4	-1.5
G (dB)	12.0	4.4
L (dB)	18.4	5.9

These calculated values may be compared with measured values. Measurements were made so as to determine the margin as a function of the percentage of locations [Guilbeau, 1979].

3.3 Variation of margin with frequency

The output of the COFDM receiver is proportional to the received mean power μ, averaged over the so-called small area.

From one small area to another, μ is distributed according to a log-normal law. Let m and s be respectively the mean and the standard deviation of 10 log μ which is distributed according to a Gaussian law.

Then margin M is the sum of the propagation margin which is the difference between the mean power under free space conditions (S_f) and the mean power actually received (m): S_f - m, and of a coverage margin which depends upon the percentage of locations where the required signal quality is to be achieved: ks

$$M = S_f - m + ks$$

k = 2.33 for 99% of small areas

k = 1.29 for 90% of small areas.

As previously indicated, S_f - m and s are simplified linear functions of the frequency f and the elevation angle α:

$$S_f - m = A + 1.93 \, f \, (\text{GHz}) - 0.052 \, \alpha \, (°)$$

$$s = 0.5 \, (B + 0.053 \, f \, (\text{GHz}) + 0.040 \, \alpha \, (°))$$

A and B being dependent on the environment and $\alpha < 45°$.

For 99% of locations, we have:

$$M = (A + 1.16 \, B) + 1.99 \, f - 0.05 \, \alpha$$

for 90% locations:

$$M = (A + 0.64 \, B) + 1.96 \, f - 0.026 \, \alpha.$$

The variations of M with respect to f (referred to 1 GHz) are not significantly different for 99% and 90% locations. They are given in Table 22, derived from the above formulas, and correspond within 0.2 dB with the values communicated to WARC-92 in the pertinent Report of the ex-CCIR (Technical and operational bases for WARC-92, Geneva 1991).

TABLE 22

Variation of the propagation margin with frequency

f (GHz)	ΔM (dB)
1	0
2	2
3	3.9

3.4 Delay spread and correlation bandwidth

Table 23 shows the maximum values of 90% delay spread and 0.5 (90%) correlation bandwidth for each environment.

TABLE 23

Maximum values of 90% delay spread and 0.5 (90%) correlation bandwidth for each environment

Environment	90% delay spread	0.5 (90%) correlation bandwidth
Rural	0.48	3.5
Suburban	2.05*	2.8
Urban	2.54	0.9
Dense	2.5	0.4

* Ignores the highest value for which no correlation bandwidth has been calculated.

At lower frequencies, high values of delay spread at 200 MHz were recorded and backscatter from mountain slopes with a maximum at VHF were noted, respectively.

This fact could indicate that for lower frequencies in rural areas lower correlation bandwidths could occur (see also § 4.4 of the present annex).

3.5 Variation of propagation margin with elevation angle

Sound-broadcasting satellite services should be able to operate over a wide range of elevation angles, ranging normally from 90° to about 5° for the geostationary satellites (GEO) or from 90° to about 60° for the highly-inclined orbit satellites (HEO).

Until quite recently, only propagation data for relatively low elevation angles have been available. In early 1990, a study on the refinements of the mobile channel from the University of Bradford has been completed in the framework of ESA "ARCHIMEDES" study. This study time provided some quantitative information on the narrow-band channel offered by the high-elevation angles. This information is reproduced below.

Table 24 summarizes the fade margins for different link availabilities, elevation angles and environments at frequency 1.5 GHz.

A word of caution should apply for the case of the elevation angle α = 80° and suburban/urban areas. Since the values contained in Table 24 for 80° do not take into account building losses, much higher margins may be required to provide a sufficient service in buildings for portable receivers.

TABLE 24

Fade margins for different elevation angles, service availabilities and environments (f = 1.5 GHz)

Margins for different elevations and service availabilities	40°				60°				80°			
	90%	95%	99%	99.9%	90%	95%	99%	99.9%	90%	95%	99%	99.9%
Open rural	0.5	0.7	0.9	1.1	0.5	0.6	0.8	0.9	0.5	0.6	0.7	0.8
Tree-shadowed	5.7	6.8	9.7	11.2	4.0	4.9	6.7	8.6	0.5	0.5	0.7	1.2
Suburban	5.8	7.1	9.0	9.9	2.1	3.1	5.5	8.3	0.5	0.8	1.2	1.5
Urban	16.9	16.6	17.6	17.6	14.6	14.6	15.1	15.6	1.6	1.8	2.9	3.8

The data from Table 24 may be interpreted in the following way:

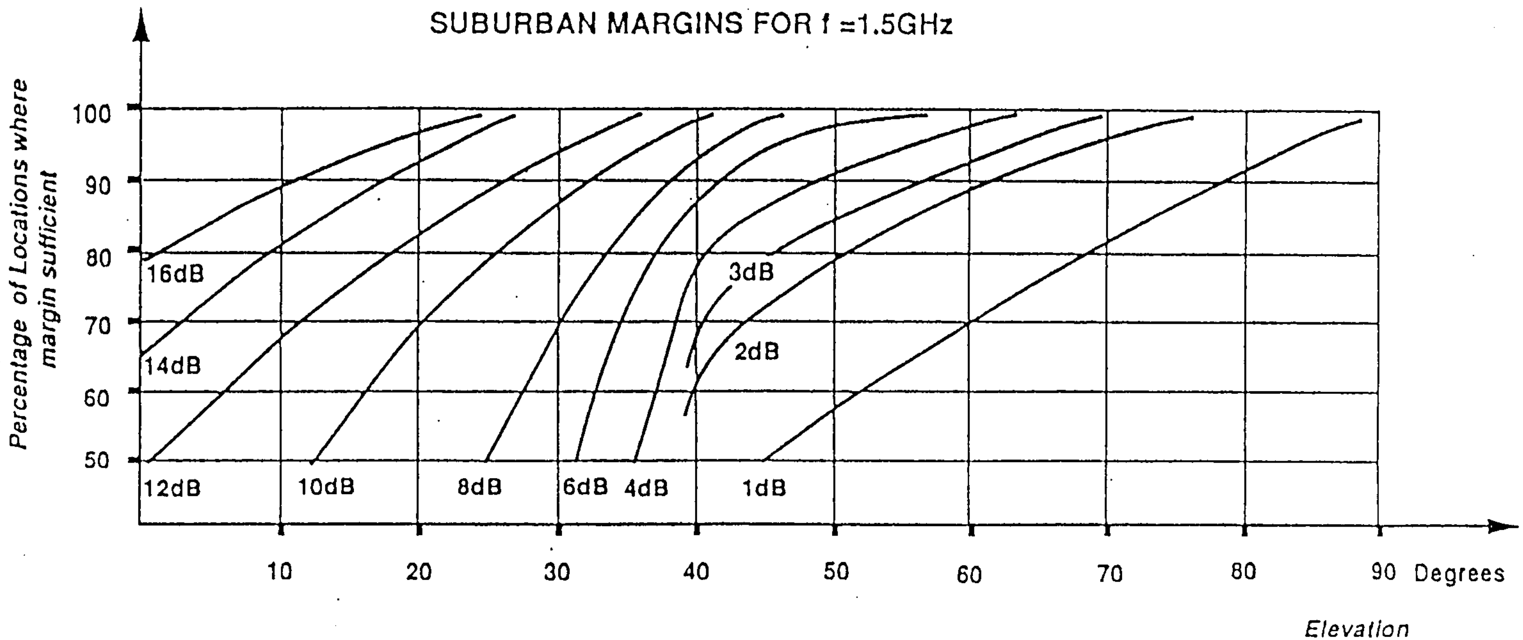
For open rural areas, about 1 dB margin seems to be sufficient to provide a service for 99% of all locations.

For suburban areas, the results are shown in Table 24. They are also depicted in Fig. 15 with a reasonable degree of precision (± approximately 1 dB). The graphs in the figure show the percentage of locations where the margin is sufficient for the suburban terrain type. For example, a margin of about 6 dB is required for a service at 90% of locations and a satellite elevation angle of 40°.

Fig. 16 gives the approximate values of the propagation margins required for urban areas at elevation angles > 40° at a frequency of 1.5 GHz.

The above results obtained by the University of Bradford (United Kingdom) have been measured by using a narrow-band digital system.

FIGURE 15


SUBURBAN MARGINS FOR f =1.5GHz
Percentage of Locations where margin sufficient
100
90
80
70
60
50
16dB
14dB
12dB
10dB
8dB
6dB
4dB
3dB
2dB
1dB
10
20
30
40
50
60
70
80
90 Degrees
Elevation

4. Frequency selectivity effects

Another important characteristic of the UHF radio propagation channel in urban and suburban mobile radio environment is the existence of multiple propagation paths with different and varying time delays. In the case of sound satellite broadcasting, the shortest (direct) path between the satellite and the portable receiver is often blocked by intervening buildings, so that propagation by way of scatter or reflection from buildings around the receiver is significant. Two cases should be considered:

- a stationary receiver; in this case, the radio channel, and thus the propagation statistics of the link, is relatively stable. The multipath propagation characteristics can be described in terms of the multipath spread and correlation bandwidth.
- a moving receiver, the propagation statistics of the radio link is a time-varying function. Different Doppler shifts are associated with scatter paths arriving at the vehicle receiver from different angles. In this context, the key terms are the Doppler spread and correlation time.

The statistical functions which describe the frequency and time selective radio link can be readily obtained by measuring the complex bandpass impulse response of the link. These statistical descriptors and parameter values set bounds on digital communication system performance parameters.

4.1 Delay spread and correlation bandwidth

Consider a statistically stationary channel first. Two spectral components of a modulated signal which are close in frequency will fade in a correlated way, i.e. the two sets of phasors resulting from a given multipath environment will be similar in amplitude and phase. As the frequency separation between the two spectral components increases, the correlation between the two sets of phasors reduces, resulting in amplitude variations (decorrelation) as a function of frequency. This is known as frequency selective fading. The bandwidth at which decorrelation occurs is termed the correlation bandwidth.

The delay power spectrum (also termed as the multipath intensity profile) and spaced-frequency correlation function constitute a Fourier transform pair (Fig. 17).

As a result of the Fourier transform, there is a relationship between correlation bandwidth of the statistically stationary channel and of the "delay spread" of the channel:

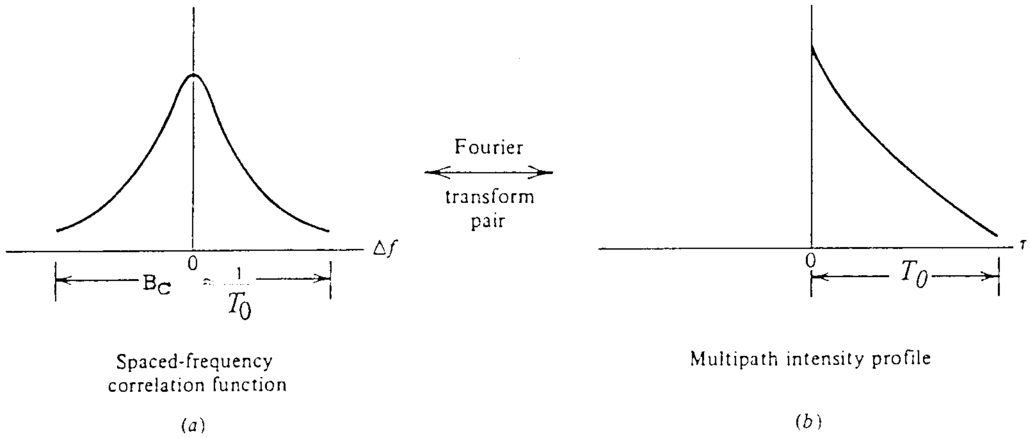
$$B_c \approx 1/T_o \qquad (12)$$

where B_c is a correlation bandwidth (Hz), and

T_o is a delay spread (s)

FIGURE 17

Relationship between T_0 and B_c



The delay spread T_0 of the channel is a measure of the width of an average power delay profile. It is defined as the square root of the second central moment of a profile m [Cox, D.C., 1972].

$$T_0 = \left[\frac{\sum_{k=1}^{M} (\tau_k - D)^2 P(\tau_k)}{\sum_{k=1}^{M} P(\tau_k)} \right]^{1/2} \qquad (13)$$

where

- k = 1, ..., M k ranges over the delay axis and M is the index of the last sample along the delay axis
- $P(\tau_k)$ an average power delay profile for a set of N consecutive individual profiles
- D average excess delay. It is defined as the first moment of the profile with respect to the first arrival delay τ_A:

$$D = \frac{\sum_{k=1}^{M} \tau_k P(\tau_k)}{\sum_{k=1}^{M} P(\tau_k)} - \tau_A \qquad (14)$$

If the correlation bandwidth is small in comparison to the bandwidth of the transmitted signal, the channel is frequency-selective. In this case, the signal is severely distorted by the channel.

On the other hand, if the correlation bandwidth is large in comparison to the bandwidth of the transmitted signal, the channel is frequency non-selective.

In order to overcome the selectivity of the channel which may cause intersymbol interference, the delay spread T_o must be much less than the symbol period T_S or, in other words, the delay-spread to symbol-period ratio, i.e. $T_r = T_o/T_S$, should be much less than 1.

The empirical relationship between the correlation bandwidth at 90% correlation and the delay spread (see Fig. 18) was obtained from [Cox, Leck, 1975]:

B_c (90%) = 90/To,

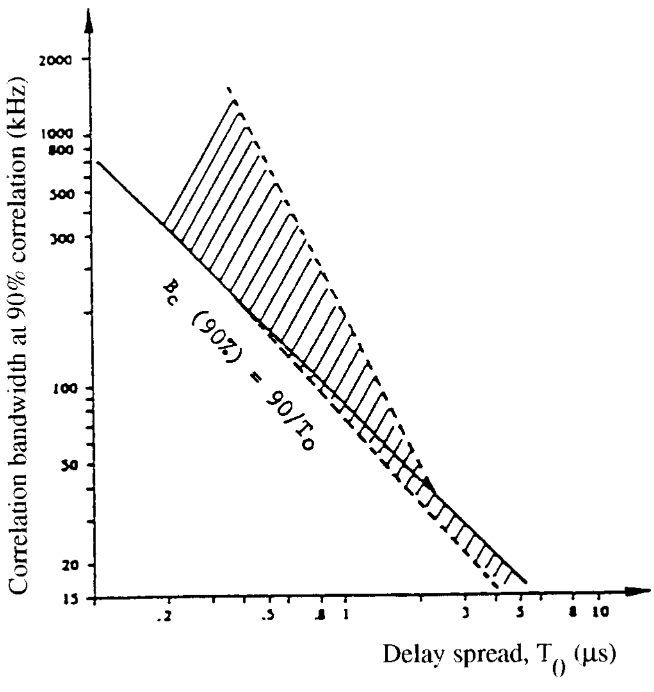
where

B_c (90%) is the correlation bandwidth at 90% correlation between two spectral components (in kHz) and

T_o is the delay spread (in µs).

FIGURE 18

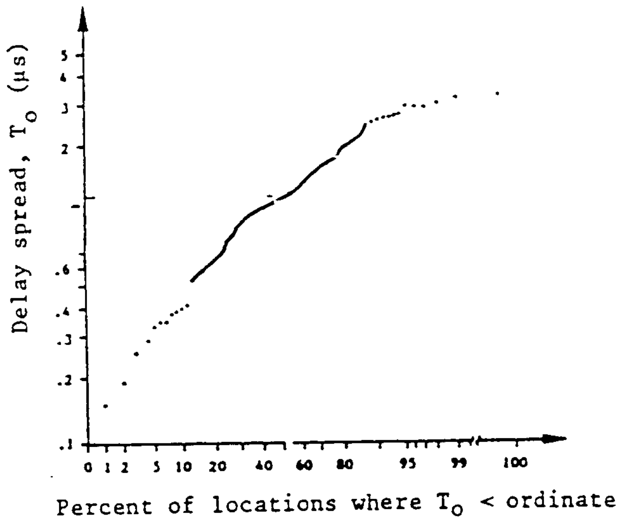
Correlation bandwidth at 90% correlation versus delay spread [Cox and Leck, 1975]



The corresponding cumulative distribution of delay spreads is shown in Fig. 19 below:

FIGURE 19

Cumulative distribution of delay spread [Cox and Leck, 1975]

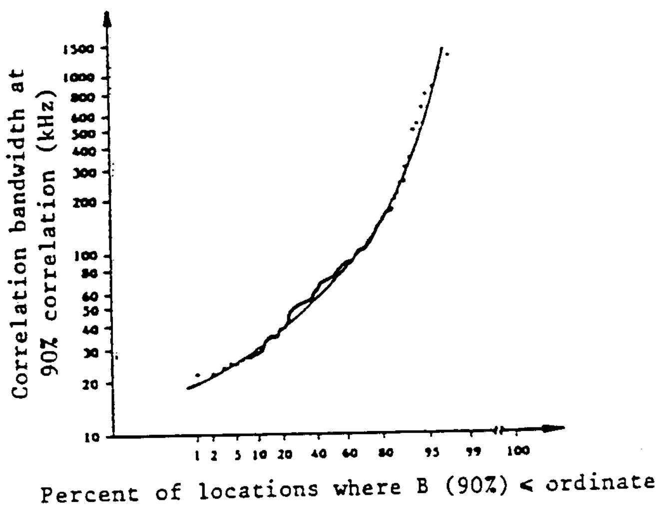


It can be deduced from the above figure that about 10 percent of small areas have $T_0 > 2.5$ μs and about 50% have $T_0 > 1.2$ μs.

The corresponding cumulative distribution for B(90%) is depicted on Fig. 20 below:

FIGURE 20

Cumulative distribution of correlation bandwidth at 90% correlation [Cox and Leck, 1975]



It can be deduced from the above figure that about 10 percent of small areas have $T_o > 2.5$ µs and about 50% have $T_o > 1.2$ µs.

The corresponding cumulative distribution for B(90%) is depicted on Fig. 20 below:

Delay spreads have been measured in residential locations and in a medium sized office building [Devasirvatham, 1986]. The worse case delay spreads of less than 325 ns were obtained when the propagation path followed line-of-sight. When there was no line-of-sight between transmitter and receiver, the delay spread increased up to 422 ns.

4.2 Doppler spread and correlation time

In the case of a moving receiver, the time variations of the propagation link result in a Doppler broadening of the received spectrum. If a pure frequency tone is transmitted, a Doppler spread B_d of the channel can be measured.

Analogous to our consideration in the previous section, a measure of the correlation time T_c of the channel could be defined:

$$T_c = 1/B_d \tag{15}$$

where T_c denotes the correlation time (s), and

B_d denotes the Doppler spread (Hz).

A slowly changing channel has a large correlation time and a small Doppler spread. Fig. 21 shows that the Doppler power spectrum and the spaced-time correlation function constitute a Fourier transform pair.

FIGURE 21

Relationship between B_d and T_c

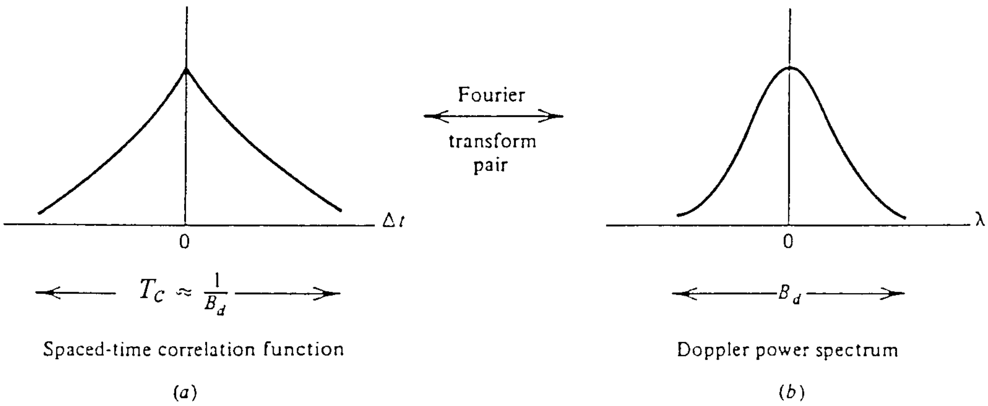


Fig. 22 shows the averaged signal envelope spectrum obtained during a time period of approximately 1 minute in a suburban area (residential with trees). A distinct frequency cut-off at around 110 Hz is visible in this figure and this value is twice the Doppler frequency f_d given by [Jongejans, 1986]:

$f_d = v/\lambda = 55$ Hz   v = 40 km/h and
f = 1.5 GHz.

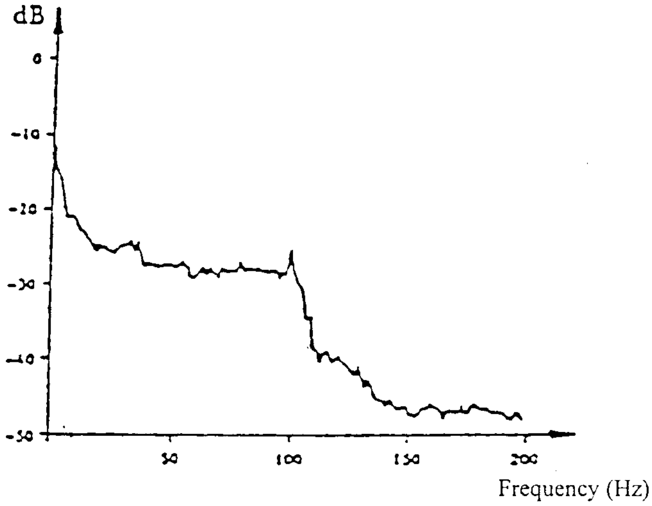
Fig. 22 shows the averaged signal envelope spectrum obtained during a time period of approximately 1 minute in a suburban area (residential with trees). A distinct frequency cut-off at around 110 Hz is visible in this figure and this value is twice the Doppler frequency f_d given by [Jongejans, 1986]:

$f_d = v/\lambda = 55$ Hz   v = 40 km/h and
f = 1.5 GHz.

This is an indication that in urban environments frequency-spreading of up to twice the Doppler frequency can be expected due to scattering from surrounding obstacles. Thus the Doppler spread B_d equals to 110 Hz.

FIGURE 22

Spectrum of signal envelope (suburban area); vehicle speed: 40 km/h, frequency: 1.5 GHz [Jongejans, 1986]



4.3 Effect of channel bandwidth in frequency selective fading

4.3.1 Measurement programme

A measurement programme was undertaken in Canada during the summer of 1991 [CCIR, 1990-94, Doc. 10-11S/36(CAN)] with the objective of providing empirical data on the effect of the channel bandwidth on the availability of service. The test procedure chosen for this experiment is based on the principle that the performance (or service availability) of an advanced digital audio broadcasting system well adapted to the severe multipath environment of mobile receivers, is mainly a function of the carrier-to-noise ratio at the receiver input. A wide and flat spectrum signal was transmitted at a centre frequency of 1 497 MHz and the received power was measured along routes in various multipath environments such as dense urban, urban, suburban and rural areas. Measurements were repeated on each test route for different receiver IF bandwidths ranging from 100 kHz - 5 MHz (3 dB). Received power levels were sampled at every 2.5 cm along the test route. This corresponds to one eighth of a wavelength, providing ample data for the analysis of the power envelope impaired by multipath fading. Measurements were carried out during summer time, in presence of heavy foliage on the deciduous trees.

4.3.2 Data reduction process

The raw data was first filtered with a moving average algorithm (161 point Hamming window, 20 λ) to separate the multipath fading component from the shadowing-multipath composite signal. The 800 metre data files were then fragmented in ten 80 metre data segments to facilitate the validation of the data. After the sorting of the data segments, valid 800 metre files were reassembled and a probability density function (pdf) was generated for each data file. The pdf's from selected data files in a given zone were cumulated and a cumulative distribution function of received power levels was calculated for each zone.

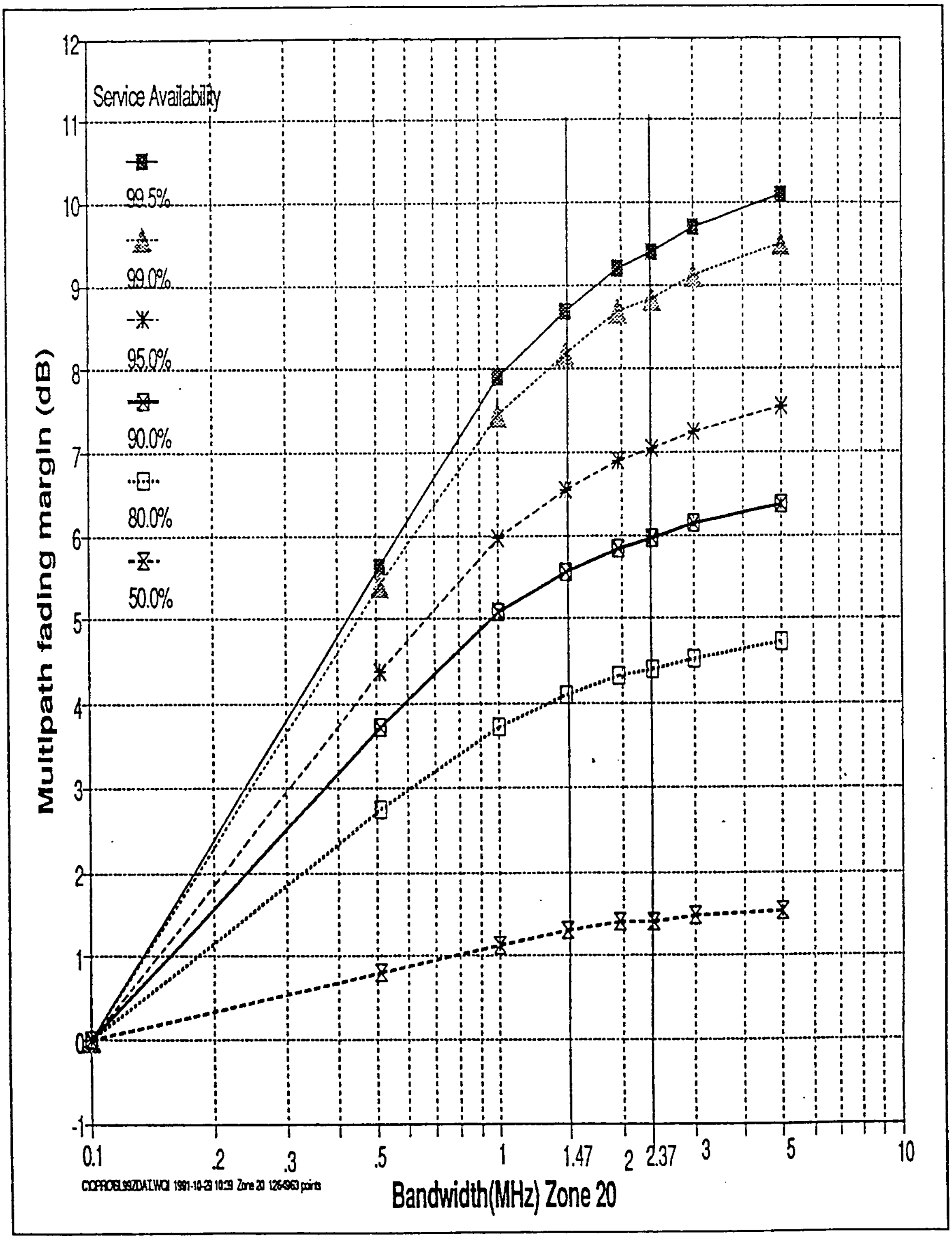
4.3.3 Results

The information about the improvement of service availability lies in the distance in decibels between the cumulative distribution curves of the different bandwidths, at specific percentages of service availability. These distances are shown in Fig. 23 showing the increasing multipath fade margin as the channel bandwidth is increased from 100 kHz - 5 MHz, in the different multipath environments. The fade margin can be interpreted as the possible saving in transmit power relative to that needed for a 100 kHz channel bandwidth system, for an equivalent service availability objective.

Fig. 23 shows that for service availability objectives lower than 50%, the improvement in fade margin remains in the order of 1.5 dB for a dense urban area. Significant improvement is observed for service availability objectives of 90% or greater. Each curve can be divided into two sections, the first part being from 100 kHz to a bandwidth value that corresponds to a knee in the curve, the second part being from the knee position to the 5 MHz bandwidth value. The criterion used to consistently locate the knee position is to find the point along the 99% service availability curve that corresponds to a 1 dB reduction of the fade margin value read at 5 MHz.

FIGURE 23

Improvement in multipath fade margin, Dense Urban, Ottawa



This method of quantifying the effect of the bandwidth on the multipath fade margin was applied to the eleven zones and the results are summarized in Table 25. This table shows the improvement in multipath fade margins as the channel bandwidth is increased from 100 kHz - 5 MHz for service availability objectives of 90% and 99%.

TABLE 25

Multipath fade margins for service availability of 90% and 99%

TYPE OF ENVIRONMENT	KNEE POSITION	TYPICAL IMPROVEMENTS IN FADE MARGIN (dB)			
		100 kHz-to-knee		Knee-to-5 MHz	
	(MHz)	90%	99%	90%	99%
DENSE URBAN	1.8	5.4	8.6	0.5	1.0
URBAN	1.6	4.5	7.0	0.6	1.0
SUBURBAN	1.9	4.1	8.1	0.6	1.0
RURAL, FOREST	1.7	3.7	6.0	0.7	1.0
RURAL, OPEN	1.1	1.2	1.8	0.7	1.0

Typically, the 90% service availability objective curves show an improvement in the order of 4 dB, from 100 kHz to the knee (1.1 to 1.9 MHz), and an improvement remaining below 0.7 dB, from the knee to the 5 MHz bandwidth value.

It appears that an appropriate choice for a channel bandwidth is a value around 2 MHz. Below 2 MHz, the multipath fading increases abruptly while above 2 MHz the improvement in fade margin is generally not very significant.

4.4 Recent multipath measurements

Insufficient data on wideband propagation characteristics has been available to allow appropriate modeling of the channel.

In order to redress the situation, a number of studies have recently been undertaken in Europe to obtain statistics for the wideband channel. Delay spread and correlation bandwidth are two important parameters which need to be considered in a wideband system, and ideally these parameters are a function of environment and elevation angle. However, to date the experiments have only been undertaken for low elevation angles (< 3°) but work is currently being undertaken within Europe to obtain wideband statistics from either an aircraft mounted transmitter or Global Positioning System (GPS) Navstar transmissions.

Table 26 consists of available wideband propagation data to-date and includes the results of the more recent wideband measurements undertaken within Europe. The data are presented as a function of frequency and environment. References for this comparison are also shown.

The main aspect of the wideband system, discussed in section 2 of the present Report, is the ability of the system to utilize reflected signals. The wideband system is therefore, to a large extent, insensitive to multipath propagation.

This fact leads to the so-called "hybrid concept" whereby, in extremely dense urban or mountainous areas which may be screened from the main satellite signal, a small terrestrial relay station using the same frequency can be used to retransmit the satellite signal and thus complete the necessary coverage. Preliminary work undertaken at a frequency of 794 MHz by CCETT (France) and verified by BBC (UK) on 531 MHz shows the hybrid system to be a viable means of extending coverage to unserved areas.

From Table 26, it can be seen that there is no reasonable agreement between researchers, both in the frequency terms for delay, delay spread and correlation bandwidth or in environment. The results shown are the subject of an extensive analysis conducted by the University of Bradford (UoB). The divergence of results indicate that measurement, analysis and general interpretation of data need to be regularized.

TABLE 26

Variation of delay, delay spread and correlation bandwidth at different frequencies and environments

Environment	Frequency MHz	90% mean delay	90% delay spread	0.5 (90%) correlation bandwidth	Notes	References
Rural	531 900 910 1 265	0.36 3.0 .-- 0.1	0.4 5.0 0.4 0.35	0.1 .-- .-- 3.5	- A - -	5 13 18 6
Suburban	436 531 880 880 900 910 910 1 265	1.77 0.47 1.0 1.0 0.65 0.19 .-- 0.1	1.81 0.54 1.30 1.0 0.6 2.5 1.2 0.4	0.1 0.6 .-- 0.1 0.1 0.07 .-- 2.8	A - - - B - - C	9 5 10 19 11 12 18 6
Urban	436 531 880 880 900 1 265	1.51 0.36 1.2 1.2 1.3 0.27	2.59 0.51 1.5 1.5 1.25 0.44	0.05 0.8 0.1 0.1 0.09 0.9	A - - - B C	9 5 10 19 11 6
Dense urban	531 900 900 900 910 1 265	0.69 1.25 0.2 2.0 2.0 0.89	0.75 1.5 1.4 2.0 2.5 1.02	0.2 0.09 .-- .-- 0.13 1.0	- B A - - C	5 11 13 8 14 6

Note A - Not exact 90% CDF values but estimated.

Note B - Figures quoted for bandwidth are actually 0.8 values.

Note C - Approximate values derived from graphs.

Returning to Table 26, it does appear that if maximum values are taken for each environment for 90% correlation bandwidth and 90% delay spread, then we can see that, in general, delay spread reduces as clutter reduces and consequently the correlation bandwidth increases as clutter reduces.

5. Other propagation experiments

5.1 Outdoor measurements

During the period 1985-1988, a series of experiments was sponsored by NASA and undertaken by the Electrical Engineering Research Laboratory of the University of Texas and the applied Physics Laboratory of The John Hopkins University in which propagation impairment effects were investigated for vehicular receivers in predominantly rural and suburban settings (see references). While the initial objectives of these experiments were to provide propagation impairment criteria to designers of planned LMSS systems and modellers of propagation effects associated with LMSS scenarios, the results are equally applicable to satellite sound broadcasting. Some of these results are found in Report 1009.

The vehicular propagation measurement programmes were performed in Central Maryland United States of America, North-Central Colorado United States of America, and South-Eastern Australia. These experiments, which were implemented with transmitters on helicopters and geostationary satellites (INMARSAT-B2, Japan's ETS-V, and INMARSAT-Pacific) were performed at UHF (870 MHz) and L-band (1.5 GHz). The satellite measurements were performed at L-band only. The specific objectives of the above tests were to assess the degrees of impairment to propagation caused by shadowing and multipath from trees and terrain for those suburban and rural regions where terrestrial cellular communication services are impractical. During these campaigns, the receiver system was located on a van outfitted with UHF and L-band antennas on its roof, and receivers and data acquisition equipment in its interior.

5.1.1 Attenuation due to roadside trees at 1.5 GHz

Cumulative fade distributions were systematically derived from helicopter-mobile and satellite-mobile measurements in the Central Maryland region. A formula was derived characterizing the cumulative fade distribution as a function of elevation angle for an overall average condition of driving along 640 km of roads exhibiting shadowing and multipath. This formulation, referred to as the "Empirical Roadside Shadowing (ERS) Model," is valid for P = 1 to 20%, and is given by:

$$F(P,\theta) = -M(\theta)\ln P + B(\theta) \text{ dB} \qquad (16)$$

where F is the fade exceeded in dB for P percentage of distance (or time), and 0 is the path elevation angle (in degrees) to the satellite. The parameters M and B are path angle dependent and are given by:

$$M(\theta) = a + b\theta + c\theta^2 \qquad (17)$$

$$B(\theta) = d\theta + e \qquad (18)$$

where

$$a = 3.44 \quad b = .0975 \tag{19}$$

$$c = -0.002 \quad d = -0.443 \quad e = 34.76$$

No physical significance should be attributed to equations (16) through (18) other than that they are in agreement with a family of angle dependent fade distributions derived from an extensive and varied data base.

In Fig. 24 a family of cumulative distributions is given (percentage versus fade exceeded) for the indicated path elevation angles. The model was found to agree with the data points at 20 degrees, 30 degrees, 45 degrees, and 60 degrees to within 0.3 dB. The Empirical Roadside Shadowing (ERS) model was further validated employing distributions acquired in Southeast Australia using transmissions from the ETS-V and INMARSAT-Pacific. Agreement between the model and the measured cumulative distribution in Australia, for more than 400 km of driving along rural and suburban roads, was well within 2 dB at all equi-probability levels.

5.1.2 Equi-probability attenuation scaling factor between L-band and UHF

Simultaneous mobile fade measurements at L-band and UHF in Central Maryland have demonstrated that the ratio of fades at equal probability levels is approximately consistent with the square root of the ratio of frequencies over this frequency interval. That is:

$$F(f_1) \approx F(f_2)\sqrt{f_1/f_2} \tag{20}$$

where $F(f_1)$ and $F(f_2)$ are the fades in dB (or dB/m) at the frequencies f_1 and f_2, respectively. More specifically, it was observed that by examining 480 km of combined simultaneously acquired UHF and L-band measurements for $f_1 = f_L = 1.5$ GHz and $f_2 = f_{UHF} = 870$ MHz that:

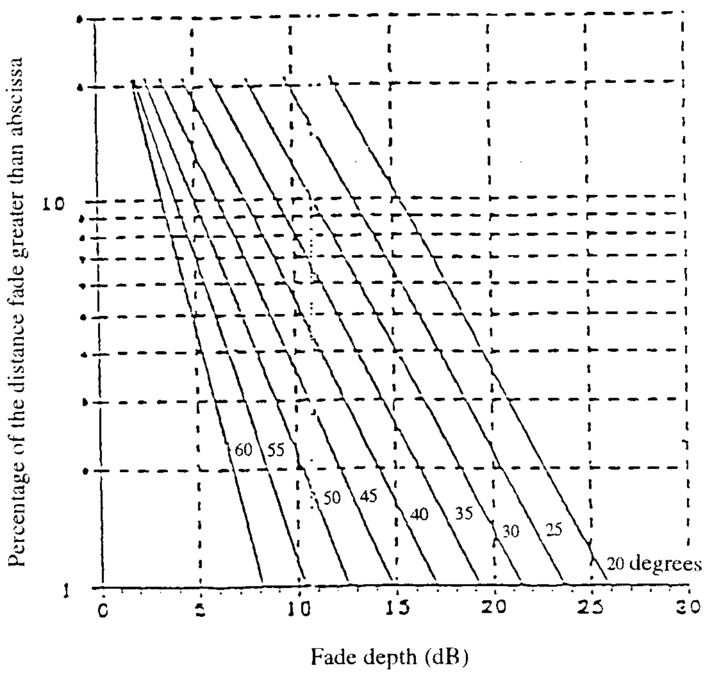
$$F(f_L) \approx 1.31F(f_{UHF}) \text{ dB} \tag{21}$$

where the multiplying coefficient 1.31 was shown to have an r.m.s. deviation of ±0.1 over a fade exceedance range from 1% to 30%.

It should be stressed that the expression (20) has been shown to be consistent with measurements at 1.5 GHz and 870 MHz. Nevertheless, in the absence of other criteria, it seems reasonable to use (20) to estimate fades over the range 500 MHz - 3 GHz.

FIGURE 24

Cumulative fade distributions at 1.5 GHz for family of path elevation angles employing the Empirical Roadside Shadowing (ERS) model



5.2 Detailed measurements inside buildings

A practical digital broadcasting service from satellites will need to be able to serve indoor receivers with modest gain antennas since this is a large fraction of the radio broadcasting market. Experiments were conducted in the United States during 1990 to obtain "fine structure" data on the radiation fields that can be expected in rooms inside buildings for typical satellite broadcasting elevation angles. The results are encouraging for radio broadcasting, mainly because a radio listener should be able to place an "indoor table model" radio in any one of many positions within a room that represents a "peak" of a time-stable radiation pattern. Simply stated, link margins need not be based upon average or "trough" levels within a building, but on "crest" values. Typically, a crest value is 5 dB or more higher than an average value for the room.

Significant results of the data analyses as the impact on BSS (sound) design are summarized below, along with a brief description of the experimental protocol and equipment. Variations in propagation losses were studied as a function of frequency (700 - 1 800 MHz, approx.), type of building, and satellite simulated elevation angle (12° to 48°).

5.2.1 Experimental aspects

Instrumentation

The measurement system makes use of an erectable 17.9 m tower attached to a van which has been outfitted with radio transmission and reception equipment as well as a data acquisition and control computer. Continuous wave (constant frequency or swept) signals from a signal generator synchronized to a microwave spectrum analyser are fed through a cable to the top of the tower, amplified, and transmitted towards the location under test. There the signals are received by an antenna which is mounted to a linear positioner about 1.4 m above ground and pointed towards the transmitter. After amplification the received power is transmitted through an 80 m cable back to the spectrum analyser in the van. The positioner can be manually oriented to allow computer controlled antenna motion along any arbitrary axis. For the measurements presented here, the receiving antenna position was varied in 16 steps of 0.05 m, resulting in a total scan distance of 0.8 m along either the vertical direction or in the horizontal plane parallel with or at right angles to the propagation path.

The measurement system is capable of determining transmission loss over a maximum frequency span from 700 to 1 800 MHz with a resolution bandwidth of between 10 kHz and 1 MHz and an overall accuracy of better than 0.5 dB. By varying the transmitter to receiver range from 15 to 75 m, elevation angles of 12° to 48° can be obtained. Both antennas are circularly polarized cavity-backed spirals with 90° half-power beamwidth and gain increasing from -2.5 to 4.5 dB over the 700 to 1 800 MHz frequency range.

5.2.2 Measurement Sites

The measurement programme encompassed four locations ranging from a metal shack to a single storey concrete block building. Many positions at each location were used.

5.2.3 Time variations

In order to assess the time-variability of the received power, repeated frequency sweeps were obtained at many measurement locations while keeping the receiving antenna stationary.

By making single frequency measurements over durations of 100 seconds, it was determined that power variations within the 1 s full sweep time of the receiver tended to be smaller than the 0.5 dB measurement accuracy of the equipment down to signal levels of about -15 dB. Variations brought about by scattering from people walking in the vicinity of the receiving antenna were also quite small, except when someone moved directly into the LOS, in which case fades of 6 to 10 dB were observed. It is concluded that time variations of near free-space-level power levels transmitted into buildings are not of primary importance in characterizing the transmission channel.

5.2.4 Building attenuation

In each of the four buildings, horizontal and vertical scans were taken at eight to twenty locations. The received power levels were analysed to derive losses at the average location and at the best location versus frequency from 700 to 1 800 MHz for bandwidths of 1, 2, 5, 9, 18, 45, and 90 MHz. As no bandwidth dependence of the losses was found, Fig. 25 gives probability contours for the signal level being less than the ordinate at 99, 90, 50, 10 and 1% at the average position in the scan for BRC 15-24 averaged over all the bandwidths listed above. The median loss increased from 5 dB at 750 MHz to 13 dB at 1 750 MHz. Assuming that the receiving antenna was placed at the best position in a scan, the median losses were reduced, varying from 1.5 dB to 7 dB over the same frequency span as noted in Fig. 26. The central percentiles at that position show less variability than those at the average position, especially at the low frequency end. Table 27 summarizes the losses observed in all buildings. By moving from the average position to the best position, the signal level can be improved by about 3 to 6 dB. The trend is for higher frequencies to suffer more attenuation when losses are moderate. In Commons, losses are rather uniformly high across the full frequency span.

After averaging over all frequencies, the probability distribution functions (PDF) at the average and best positions were calculated for each building, and the results for the Metal Shack have been plotted against a normal probability scale in Figs. 27 and 28. The means and standard deviations derived with linear regressions are summarized in Table 28.

TABLE 27

Median power levels as a function of frequency

	Average Position	Best Position
Building	750 ...... 1 750 MHz	750 ...... 1 750 MHz
BRC 16-4	-5 ...... -11 dB	-2 ...... -6 dB
BRC 15-24	-5 ...... -14 dB	-2 ...... -5 dB
Metal Shack	-9 ...... -11 dB	-5 ...... -6 dB
Commons	-17 ...... -18 dB	-12 ...... -13 dB

TABLE 28

Signal distributions at the average and best position

	Average Position		Best Position	
Building	Mean	STD	Mean	STD
BRC 16-4	-7.9 dB	5.5 dB	-4.2 dB	4.2 dB
BRC 15-24	-9.1 dB	4.4 dB	-5.4 dB	3.7 dB
Metal Shack	-9.7 dB	6.3 dB	-5.2 dB	4.9 dB
Commons	-15.4 dB	8.4 dB	-9.7 dB	6.7 dB

5.2.5 Frequency diversity

Variations of the propagation loss with frequency limit the coherence bandwidth of a transmission channel. Both frequency-dependent absorption or multipath interference can be the cause of loss of coherence. In the four test buildings multipath delays tended to be less than a few hundred nanoseconds for received signal levels within about 15 dB of the free-space level. Hence, systems with bandwidths narrower than about 1 MHz would be much less affected by loss of coherence. This observation has been borne out with some of the measurements made with a resolution bandwidth of 10 kHz.

5.2.6 Frequency variations

In light of the demonstrated frequency insensitivity of multipath effects, increased losses at higher frequencies are believed to be due to greater absorption by the walls of the buildings studied. Of all the parameters that were measured, only building attenuation showed a clear frequency dependence.

FIGURE 25

Probability contours for the signal level being less than the ordinate at 99, 90, 50, 10 and 1% at the average position in the scan for BRC 15-24

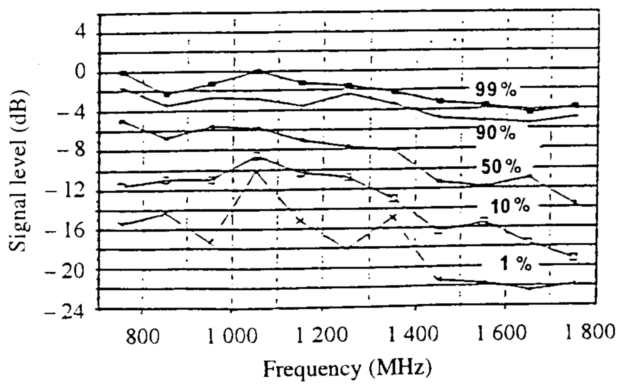
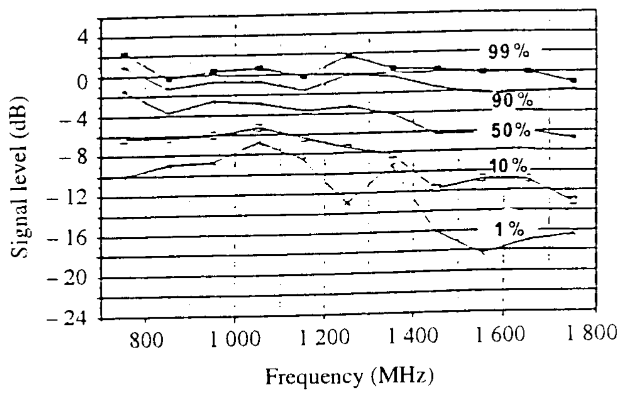


FIGURE 26

Probability contours for the signal level being less than the ordinate at 99, 90, 50, 10 and 1% at the best position in the scan for BRC 15-24



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ANNEX 3

Digital System A

1. Introduction

Digital System A is designed to provide high-quality, multi-service digital radio broadcasting for reception by vehicular, portable and fixed receivers. It is designed to operate at any frequency up to 3 000 MHz for terrestrial, satellite, hybrid (satellite and terrestrial), and cable broadcast delivery. The System is also designed as a flexible, general-purpose Integrated Services Digital Broadcasting (ISDB) system which can support a wide range of source and channel coding options, sound-programme associated data and independent data services, in conformity with the flexible and broad-ranging service and system requirements given in Recommendations ITU-R BO.789 and ITU-R BS.774, supported by Reports ITU-R BS.1203-2 and the present Report.

The system is a rugged, yet highly spectrum and power-efficient sound and data broadcasting system. It uses advanced digital techniques to remove redundancy and perceptually irrelevant information from the audio source signal, then it applies closely-controlled redundancy to the transmitted signal for error correction. The transmitted information is then spread in both the frequency and time domains so that a high quality signal is obtained in the receiver, even when working in conditions of severe multipath propagation, whether stationary or mobile. Efficient spectrum utilization is achieved by interleaving multiple programme signals and a special feature of frequency reuse permits broadcasting networks to be extended, virtually without limit, using additional transmitters all operating on the same radiated frequency.

A conceptual diagram of the emission part of the System is shown in Fig. 29.

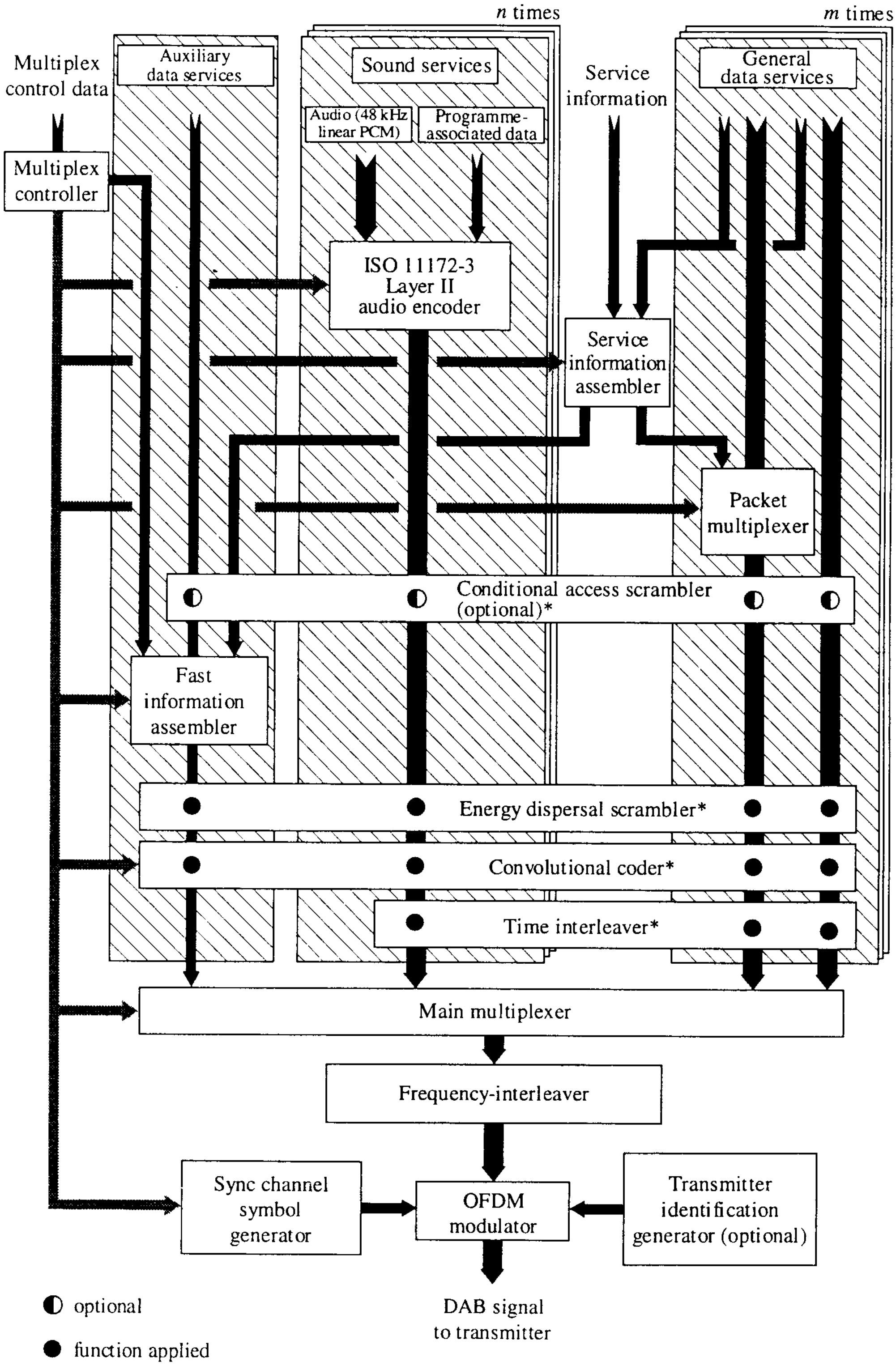
Digital System A has been developed by the Eureka 147 (DAB) Consortium and is known as the Eureka DAB System. It has been actively supported by the EBU in view of introducing digital sound broadcasting services in Europe in 1995. Since 1988, the System has been successfully demonstrated and extensively tested in Europe, Canada, the United States and in other countries worldwide. In this Annex, Digital System A is referred to as "the System". The full system specification will be available as a European Telecommunications Standard.

2. Use of a layered model

The System is capable of complying with the ISO Open System Interconnection (OSI) basic reference model described in ISO 7498 (1984). The use of this model is recommended in draft new Recommendation ITU-R BT. [Doc.11/67] and Report ITU-R BT.1207, and a suitable interpretation for use with layered broadcasting systems is given in the Recommendation. In accordance with this guidance, the System will be described in relation to the layers of the model, and the interpretation applied here is illustrated in Table 29.

FIGURE 29

Conceptual diagram of the transmission part of the system



* These processors operate independently on each service channel.

OFDM: orthogonal frequency division multiplex

D01

TABLE 29

Interpretation of the OSI layered model

Name of layer	Description	Features specific to the System
Application layer	Practical use of the system	System facilities Audio quality Transmission modes
Presentation layer	Conversion for presentation	Audio encoding & decoding Audio presentation Service information
Session layer	Data selection	Programme selection Conditional access
Transport layer	Grouping of data	Programme services Main service multiplex Ancillary data Association of data
Network layer	Logical channel	ISO audio frames Programme associated data
Data link layer	Format of the transmitted signal	Transmission frames Synchronization
Physical layer	Physical (radio) transmission	Energy dispersal Convolutional encoding Time interleaving Frequency interleaving Modulation by 4-DPSK OFDM Radio transmission

Descriptions of many of the techniques involved are most easily given in relation to the operation of the equipment at the transmitter, or at the central point of a distribution network in the case of a network of transmitters.

The fundamental purpose of the System is to provide sound programmes to the radio listener, so the order of sections in the following description will start from the application layer (use of the broadcast information), and proceed downwards to the physical layer (the means for radio transmission).

3. Application layer

This layer concerns the use of the System at the application level. It considers the facilities and audio quality which the System provides and which broadcasters can offer to their listeners, and the different transmission modes.

3.1 Facilities offered by the System

The System provides a signal which carries a multiplex of digital data, and this conveys several programmes at the same time. The multiplex contains audio programme data, and ancillary data comprising Programme-Associated Data (PAD), Multiplex Configuration Information (MCI) and Service Information (SI). The multiplex may also carry general data services which may not be related to the transmission of sound programmes.

In particular, the following facilities are made available to users of the System:

a) the audio signal (i.e. the programme) being provided by the selected programme service;

b) the optional application of receiver functions, for example dynamic range control, which may use ancillary data carried with the programme;

c) a text display of selected information carried in the SI. This may be information about the selected programme, or about others which are available for optional selection;

d) options which are available for selecting other programmes, other receiver functions, and other SI;

e) one or more general data services, for example a Traffic Message Channel (TMC).

The System includes facilities for conditional access, and a receiver can be equipped with digital outputs for audio and data signals.

3.2 Audio quality

Within the capacity of the multiplex, the number of programme services and, for each, the presentation format (e.g. stereo, mono, surround-sound, etc.), the audio quality and the degree of error protection (and hence ruggedness) can be chosen to meet the needs of the broadcasters.

The following range of options is available for the audio quality:

a) very high quality, with audio processing margin;

b) subjectively transparent quality, sufficient for the highest quality broadcasting;

c) high quality, equivalent to good FM service quality;

d) medium quality, equivalent to good AM service quality;

e) speech-only quality.

The System provides full quality reception within the limits of transmitter coverage; beyond these limits reception degrades in a subjectively graceful manner.

3.3 Transmission modes

The System has 3 alternative transmission modes which allow the use of a wide range of transmitting frequencies up to 3 GHz. These transmission modes have been designed to cope with Doppler spread and delay spread, for mobile reception in presence of multipath echoes.

The following table gives the constructive echo delay and nominal frequency range for mobile reception. The noise degradation at the highest frequency and in the most critical multipath condition, occurring infrequently in practice, is equal to 1 dB at 100 km/h.

Parameter	Mode I	Mode II	Mode III
Guard interval duration:	246 µs	62 µs	31 µs
Constructive echo delay up to:	300 µs	75 µs	37.5 µs
Nominal frequency range (for mobile reception) up to:	375 MHz	1.5 GHz	3 GHz

From this table, it can be seen that the use of higher frequencies imposes a greater limitation on the maximum echo delay. Mode I is most suitable for a terrestrial Single-Frequency Network (SFN), because it allows the greatest transmitter separations. Mode II is most suitable for local radio applications requiring one terrestrial transmitter, and hybrid satellite/terrestrial transmission up to 1.5 GHz. However, Mode II can also be used for a medium-to- large scale SFN (e.g. at 1.5 GHz) by inserting, if necessary, artificial delays at the transmitters and/or by using directive transmitting antennas. Mode III is most appropriate for satellite and complementary terrestrial transmission at all frequencies up to 3 GHz.

Mode III is also the preferred mode for cable transmission up to 3 GHz.

4. Presentation layer

This layer concerns the conversion and presentation of the broadcast information.

4.1 Audio source encoding

The audio source encoding method used by the System is ISO/IEC MPEG-Audio Layer II, given in the ISO Standard 11172-3. This subband coding compression system is also known as the MUSICAM system.

The System accepts a number of PCM audio signals at a sampling rate of 48 kHz with programme-associated data (PAD). The number of possible audio sources depends on the bit rate and the error protection profile. The audio encoder can work at 32, 48, 56, 64, 80, 96, 112, 128, 160 or 192 kbit/s per monophonic channel. In stereophonic or dual channel mode, the encoder produces twice the bit rate of a mono channel.

The different bit-rate options can be exploited by broadcasters depending on the intrinsic quality required and/or the number of sound programmes to be provided. For example, the use of bit-rates greater than or equal to 128 kbit/s for mono, or greater than or equal to 256 kbit/s for a stereo programme, provides not only very high quality, but also some processing margin, sufficient for further multiple encoding/decoding processes, including audio post-processing. For high-quality broadcasting purposes, a bit-rate of 128 kbit/s for mono or 256 kbit/s for stereo is preferred, giving fully transparent audio quality. Even the bit-rate of 192 kbit/s per stereo programme generally fulfils the EBU requirement for digital audio bit-rate reduction systems[*]. A bit-rate of 96 kbit/s for mono gives good sound quality, and 48 kbit/s can provide roughly the same quality as normal AM broadcasts. For some speech-only programmes, a bit-rate of 32 kbit/s may be sufficient where the greatest number of services is required within the system multiplex.

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[*] See EBU contribution JIWP 10-CMTT/1-7(Rev. 1) (October 1990) entitled: "Digital audio bit-rate reduction systems requirements for broadcast emission and primary distribution".

A block diagram of the functional units in the audio encoder is given in Fig. 30. The input PCM audio samples are fed into the audio encoder. One encoder is capable of processing both channels of a stereo signal, although it may, optionally, be presented with a mono signal. A polyphase filter bank divides the digital audio signal into 32 subband signals, and creates a filtered and sub-sampled representation of the input audio signal. The filtered samples are called subband samples. A perceptual model of the human ear creates a set of data to control the quantizer and coding. These data can be different, depending on the actual implementation of the encoder. One possibility is to use an estimation of the masking threshold to obtain these quantizer control data. Successive samples of each subband signal are grouped into blocks, then in each block, the maximum amplitude attained by each subband signal is determined and indicated by a scale factor. The quantizer and coding unit creates a set of coding words from the subband samples. These processes are carried out during ISO audio frames, which will be described in the Network layer.

4.2 Audio decoding

Decoding in the receiver is straightforward and economical using a simple signal processing technique, requiring only demultiplexing, expanding and inverse-filtering operations. A block diagram of the functional units in the decoder is given in Fig. 31.

The ISO audio frame is fed into the ISO/MPEG-Audio Layer II decoder, which unpacks the data of the frame to recover the various elements of information. The reconstruction unit reconstructs the quantized subband samples, and an inverse filter bank transforms the subband samples back to produce digital uniform PCM audio signals at 48 kHz sampling rate.

FIGURE 30

Block diagram of the basic system audio encoder

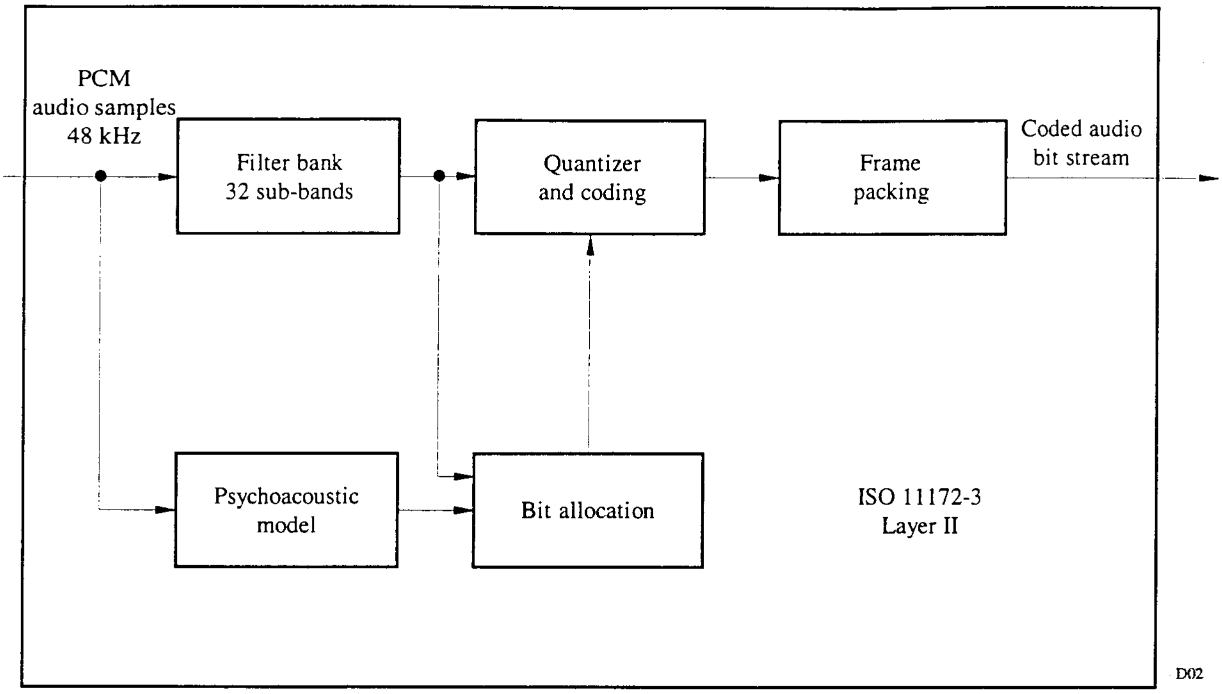
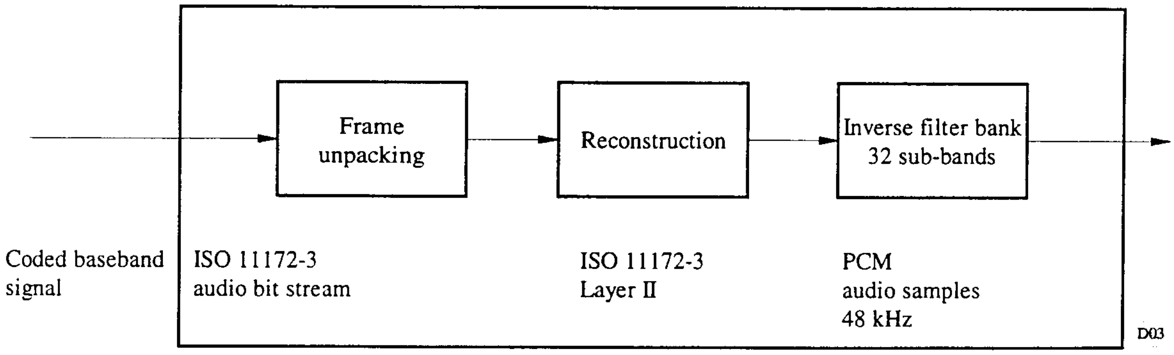


FIGURE 31

Block diagram of the basic system audio encoder



4.3 Audio presentation

Audio signals may be presented monophonically or stereophonically, or audio channels may be grouped for surround-sound. Programmes may be linked to provide the same programme simultaneously in a number of different languages. In order to satisfy listeners in both Hi-Fi and noisy environments, the broadcaster can optionally transmit a Dynamic Range Control (DRC) signal which can be used in the receiver in a noisy environment to compress the dynamic range of the reproduced audio signal. Note that this technique can also be beneficial to listeners with impaired hearing.

4.4 Presentation of Service Information

With each programme transmitted by the System, the following elements of Service Information (SI) can be made available for display on a receiver:

- basic programme label (i.e. the name of the programme);
- time and date;
- cross-reference to the same, or similar programme (e.g. in another language) being transmitted in another ensemble or being simulcast by an AM or FM service;
- extended service label for programme-related services;
- programme information (e.g. the names of performers);
- language;
- programme type (e.g. news, sport, music, etc.);
- transmitter identifier;
- Traffic Message Channel (TMC, which may use a speech synthesizer in the receiver).

Transmitter network data can also be included for internal use by broadcasters.

5. Session layer

This layer concerns the selection of, and access to, broadcast information.

5.1 Programme selection

In order that a receiver can gain access to any or all of the individual services with a minimum overall delay, information about the current and future content of the multiplex is carried by the Fast Information Channel (FIC). This Information is the MCI, which is machine-readable data. Data in the FIC are not time-interleaved, so the MCI is not subject to the delay inherent in the time-interleaving process applied to audio and general data services. However, these data are repeated frequently to ensure their ruggedness. When the multiplex configuration is about to change, the new information, together with the timing of the change is sent in advance in the MCI.

The user of a receiver can select programmes on the basis of textual information carried in the SI, using the programme service name, the programme type identity or the language. The selection is then implemented in the receiver using the corresponding elements of the MCI.

If alternative sources of a chosen programme service are available and an original digital service becomes untenable, then linking data carried in the SI (i.e. the ’cross reference’) may be used to identify an alternative (e.g. on an FM service) and switch to it. However, in such a case, the receiver will switch back to the original service as soon as reception is possible.

5.2 Conditional access

Provision is made for both synchronization and control of conditional access.

Conditional access can be applied independently to the service components (carried either in the MSC or FIC), services or the whole multiplex.

6. Transport layer

This layer concerns the identification of groups of data as programme services, the multiplexing of data for those services and the association of elements of the multiplexed data.

6.1 Programme services

A programme service generally comprises an audio service component and optionally additional audio and/or data service components, provided by one service provider. The whole capacity of the multiplex may be devoted to one service provider (e.g. broadcasting five or six high-quality sound programme services), or it may be divided amongst several service providers (e.g. collectively broadcasting some twenty medium quality programme services).

6.2 Main service multiplex

With reference to Fig. 29, the data representing each of the programmes being broadcast (digital audio data with some ancillary data, and maybe also general data) are subjected to convolutional encoding (see § 9.2) and time-interleaving, both for error protection. Time-interleaving improves the ruggedness of data transmission in a changing environment (e.g. reception by a moving vehicular receiver) and imposes a predictable transmission delay. The interleaved and encoded data are then fed to the main service multiplexer where, each 24 ms, the data are gathered in sequence into the multiplex frame. The combined bit-stream output from the multiplexer is known as the Main Service Channel (MSC) which has a gross capacity of 2.3 Mbit/s. Depending on the chosen code rate (which can be different from one service component to another), this gives a net bit rate ranging from approximately 0.8 to 1.7 Mbit/s, through a 1.5 MHz bandwidth. The main service multiplexer is the point at which synchronized data from all of the programme services using the multiplex are brought together.

General data may be sent in the MSC as an unstructured stream or organized as a packet multiplex where several sources are combined. The data rate may be any multiple of 8 kbit/s, synchronized to the System multiplex, subject to sufficient total multiplex capacity, taking into account the demand for audio services.

The Fast Information Channel (FIC) is external to the MSC and is not time-interleaved.

6.3 Ancillary data

There are three areas where ancillary data may be carried within the System multiplex:

a) the FIC, which has limited capacity, depending on the amount of essential MCI included,

b) there is special provision for a moderate amount of PAD to be carried within each audio channel,

c) all remaining ancillary data are treated as a separate service within the MSC. The presence of this information is signalled in the MCI.

6.4 Association of data

A precise description of the current and future content of the MSC is provided by the MCI, which is carried by the FIC. Essential items of SI which concern the content of the MSC (i.e. for program selection) must also be carried in the FIC. More extensive text, such as a list of all the day's programs, must be carried separately as a general data service. Thus, the MCI and SI contain contributions from all of the programs being broadcast.

The PAD, carried within each audio channel, comprises mainly the information which is intimately linked to the sound program and therefore cannot be sent in a different data channel which may be subject to a different transmission delay.

7. Network layer

This layer concerns the identification of groups of data as programmes.

7.1 ISO audio frames

The processes in the audio source encoder are carried out during ISO audio frames of 24 ms duration. The bit allocation, which varies from frame to frame, and the scale factors are coded and multiplexed with the subband samples in each ISO audio frame. The frame packing unit (see Fig. 30) assembles the actual bit stream from the output data of the quantizer and coding unit, and adds other information, such as header information, CRC words for error detection, and PAD, which travel along with the coded audio signal. Each audio channel contains a PAD channel having a variable capacity (generally at least 2 kbit/s), which can be used to convey information which is intimately linked to the sound program. Typical examples are lyrics, speech/music indication and Dynamic Range Control (DRC) information.

The resulting audio frame carries data representing 24 ms duration of stereo (or mono) audio, plus the PAD, for a single programme and complies with the ISO 11172-3 Layer II format, so it can be called an ISO frame. This allows the use of an ISO/MPEG-Audio Layer II decoder in the receiver.

8. Data link layer

This layer provides the means for receiver synchronization.

8.1 The transmission frame

In order to facilitate receiver synchronization, the transmitted signal is built up with a regular frame structure (see Fig. 32). The transmission frame comprises a fixed sequence of symbols. The first is a null symbol to provide a coarse synchronization (when no RF signal is transmitted), followed by a fixed reference symbol to provide a fine synchronization, AGC, AFC and phase reference functions in the receiver; these symbols make up the synchronization channel. The next symbols are reserved for the FIC, and the remaining symbols provide the MSC. The total frame duration T_F is either 96 ms or 24 ms, depending on the transmission mode as given in Table 30 below.

FIGURE 32

Multiplex frame structure

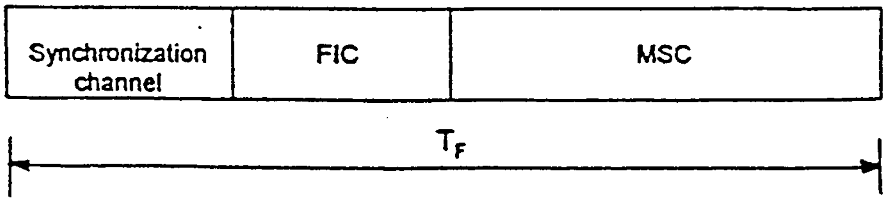


TABLE 30

Transmission parameters of the System

	Mode I	Mode II	Mode III
T_F	96 ms	24 ms	24 ms
T_{NULL}	1.297 ms	324 µs	168 µs
T_S	1.246 ms	312 µs	156 µs
t_s	1 ms	250 µs	125 µs
Δ	246 µs	62 µs	31 µs
N	1 536	384	192

The following notation is used:

T_F total frame duration

T_{NULL} null symbol duration

T_s overall symbol duration

t_s useful symbol duration

Δ guard interval duration

$$T_s = t_s + \Delta$$

Each audio service within the MSC is allotted a fixed time slot in the frame.

9. The physical layer

This layer concerns the means for radio transmission (i.e. the modulation scheme and the associated error protection).

9.1 Energy dispersal

In order to ensure appropriate energy dispersal in the transmitted signal, the individual sources feeding the multiplex are scrambled.

9.2 Convolutional encoding

Convolutional encoding is applied to each of the data sources feeding the multiplex to ensure reliable reception. The encoding process involves adding deliberate redundancy to the source data bursts (using a constraint length of 7). This gives "gross" data bursts.

In the case of an audio signal, greater protection is given to some source-encoded bits than others, following a preselected pattern known as the Unequal Error Protection (UEP) profile. The average code rate, defined as the ratio of the number of source-encoded bits to the number of encoded bits after convolutional encoding, may take a value from 1/3 (the highest protection level) to 3/4 (the lowest protection level). Different average code rates can be applied to different audio sources, subject to the protection level required and the bit-rate can be applied to different audio sources, subject to the protection level required and the bit-rate of the source-encoded data. For example, the protection level of audio services carried by cable networks may be lower than that of services transmitted in radio-frequency channels.

General data services are convolutionally encoded using one of a selection of uniform rates. Data in the FIC are encoded at a constant 1/3 rate.

9.3 Time interleaving

Time interleaving of interleaving depth of 16 frames is applied to the convolutionally encoded data in order to provide further assistance to a mobile receiver.

9.4 Frequency interleaving

In the presence of multipath propagation, some of the carriers are enhanced by constructive signals, while others suffer destructive interference (frequency selective fading). Therefore, the System provides frequency interleaving by a re-arrangement of the digital bit stream amongst the carriers, such that successive source samples are not affected by a selective fade. When the receiver is stationary, the diversity in the frequency domain is the prime means to ensure successful reception.

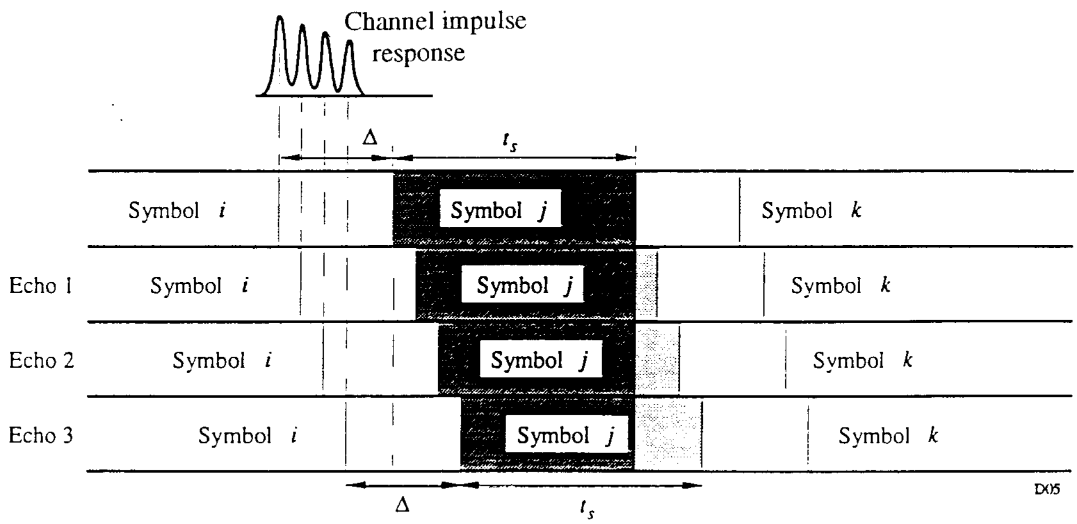
9.5 Modulation by 4-DPSK OFDM

The System uses 4-DPSK OFDM (Orthogonal Frequency Division Multiplex). This scheme meets the exacting requirements of high bit-rate digital broadcasting to mobile, portable and fixed receivers, especially in multipath environments.

The basic principle consists of dividing the information to be transmitted into a large number of bit-streams having low bit-rates individually, which are then used to modulate individual carriers. The corresponding symbol duration becomes larger than the delay spread of the transmission channel. In the receiver any echo shorter than the guard interval will not cause inter-symbol interference but rather contribute positively to the received power (see Fig. 33). The large number N of carriers is known collectively as an ensemble.

FIGURE 33

Constructive contribution of echoes



In the presence of multipath propagation, some of the carriers are enhanced by constructive signals, while others suffer destructive interference (frequency selective fading). Therefore, the System includes a redistribution of the elements of the digital bit stream in time and frequency, such that successive source samples are affected by independent fades. When the receiver is stationary, the diversity in the frequency domain is the only means to ensure successful reception; the time diversity provided by time-interleaving does not assist a static receiver. For the System, multipath propagation is a form of space-diversity and is considered to be a significant advantage, in stark contrast to conventional FM or narrow-band digital systems where multipath propagation can completely destroy a service.

In any system able to benefit from multipath, the larger the transmission channel bandwidth, the more rugged the system. In the System, an ensemble bandwidth of 1.5 MHz was chosen to secure the advantages of the wideband technique, as well as to allow planning flexibility. Table 30 also indicates the number of COFDM carriers within this bandwidth for each transmission mode.

A further benefit of using COFDM is that high spectrum and power efficiency can be obtained with single frequency networks for large area coverage and also for city area dense networks. Any number of transmitters providing the same programmes may be operated on the same frequency, which also results in an overall reduction in the required operating powers. As a further consequence distances between different service areas are significantly reduced.

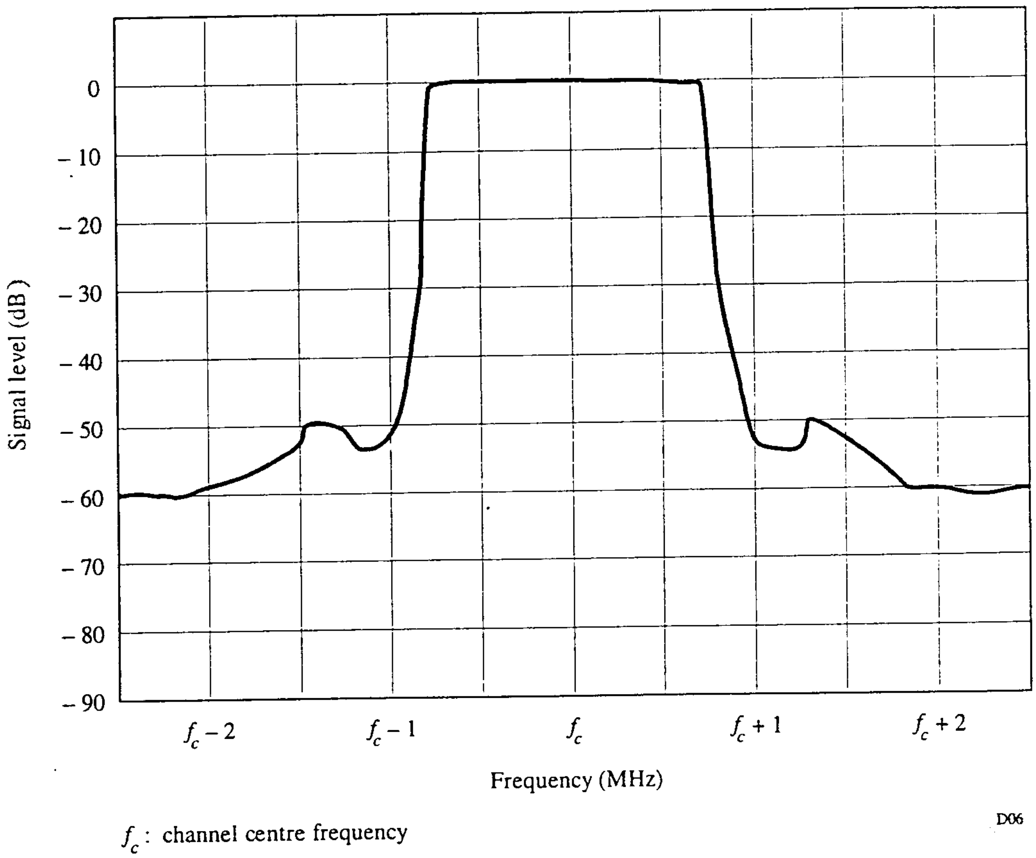
Because echoes contribute to the received signal, all types of receiver (i.e. portable, home and vehicular) may utilize simple, non-directional antennas.

9.6 Spectrum of the RF-signal

The spectrum of the system ensemble is shown in fig. 34.

FIGURE 34

Example of spectrum of the RF signal



10. RF performance characteristics of Digital System A

RF evaluation tests have been carried out on Digital System A using Mode I at 226 MHz and Mode II at 1 500 MHz for a variety of conditions representing mobile and fixed reception. Measurements of BER vs. C/N were made on a data channel using the following conditions:

D = 64 kbit/s, R = 0.5

D = 24 kbit/s, R = 0.375

where D is the source data rate and R is the average channel code rate.

10.1 BER vs. C/N (in 1.5 MHz) in a Gaussian channel at 226 MHz

Additive, Gaussian white noise was added to set the C/N at the input of the receiver. The results are shown in Fig. 35. As an example, for R = 0.5, the measured results can be compared with those from a software simulation, to show the inherent performance of the system. It can be seen that an implementation margin of less than 0.5 dB is obtained at a bit-error ratio (BER) of 10^{-4}.

10.2 BER vs. C/N (in 1.5 MHz) in a Rayleigh channel at 226 MHz

Measurements of BER vs. C/N were made on a data channel (D = 64 kbit/s, R = 0.5), using a fading channel simulator.

The results are shown in Fig. 36. For the example of a Rayleigh channel with a rural profile and the receiver travelling at 130 km/h, the measured results (curve b)) may be compared with those of a software simulation (curve a)). The difference is less than 3 dB at a BER of 10^{-4}. Curve c) illustrates typical urban performance at relatively low speed, but in a highly frequencydispersive channel. Curve d) illustrates the performance in a representative single frequency network in bad conditions, where signals are received with delays up to 600 us (corresponding to 180 km excess path length).

10.3 BER vs. C/N (in 1.5 MHz) in a Rayleigh channel at 1 500 MHz

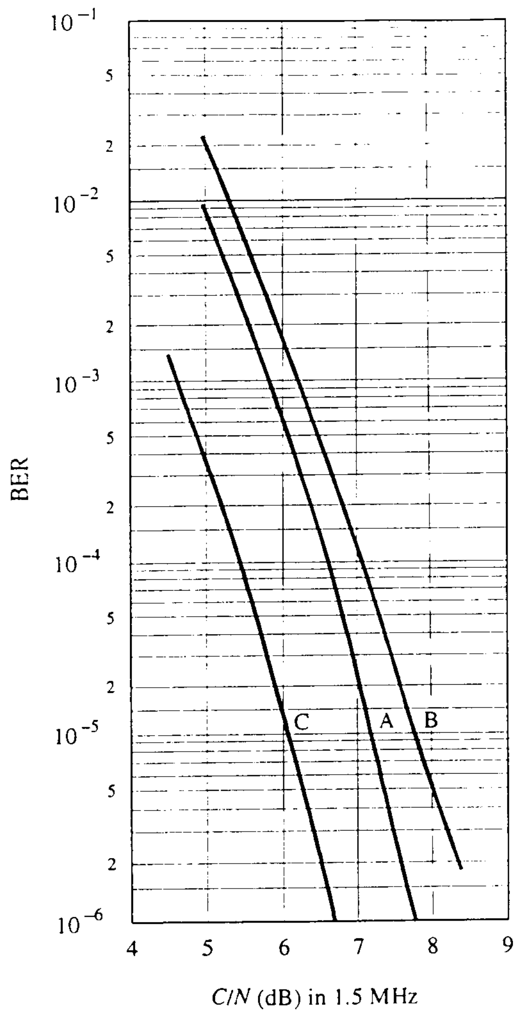
Measurements of BER vs. C/N were made on a data channel using a fading channel simulator. The results are shown in Fig. 37.

10.4 Audio service availability

Provisional assessments of sound quality indicate that it is not perceptibly impaired if the BER is less than 10^{-4}.

FIGURE 35

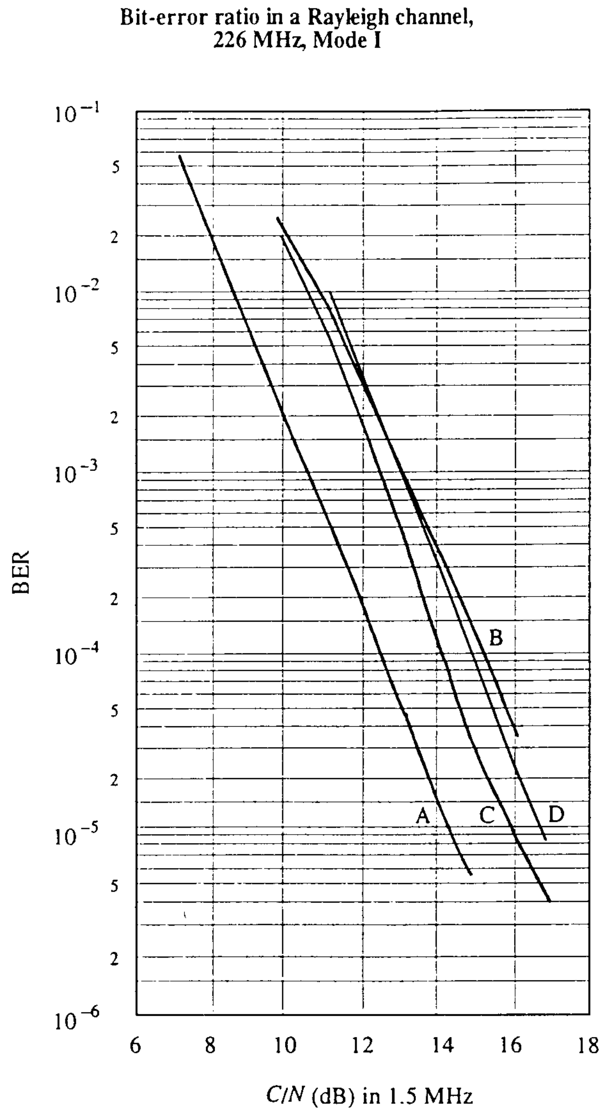
Bit-error ratio in a Gaussian channel,
226 MHz, Mode I



Curves A: R = 0.5 (software simulation)
B: R = 0.5
C: R = 0.375

D07

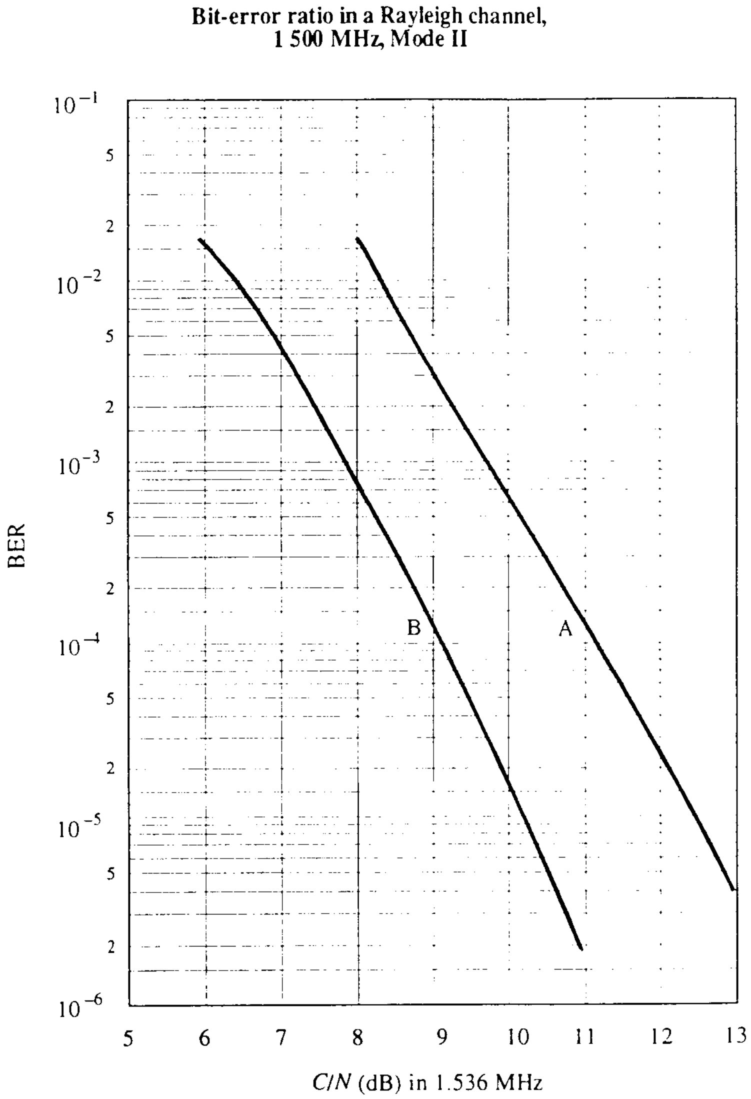
FIGURE 36



Curves A: R = 0.5, rural, 130 km/h (software simulation)
B: R = 0.5, rural, 130 km/h
C: R = 0.5, urban, 15 km/h
D: R = 0.5, SFN, 130 km/h

D08

FIGURE 37



Curves A: R = 0.5, urban, 15 km/h
B: R = 0.375, urban, 15 km/h

D09

APPENDIX 1

(to Annex 3)

Computer simulations of system performance (Digital System A)

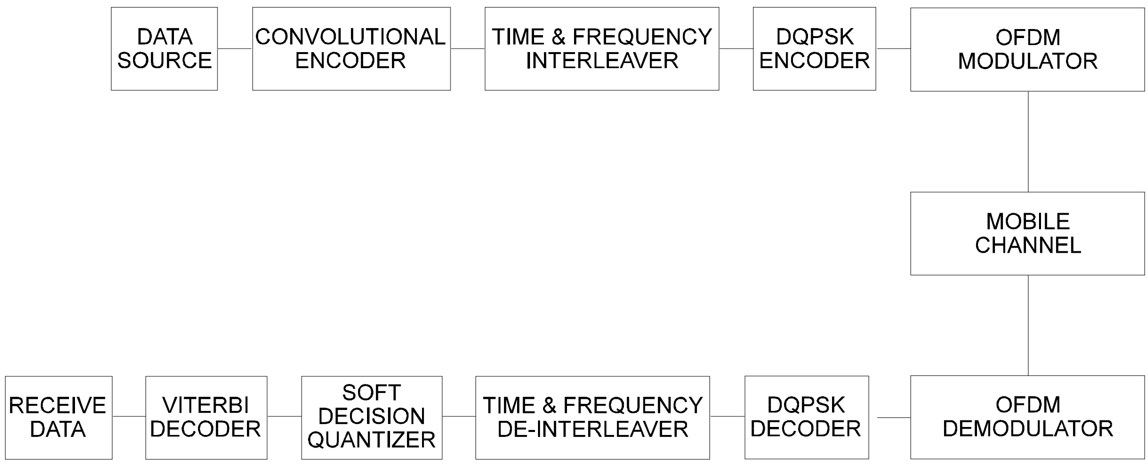
1. Computer simulation model

1.1 General model

A block diagram of the model used for the analysis and simulation of the COFDM scheme is shown in Fig. 38. The data source generates a pseudo-random binary sequence. The bit generated at any given time is independent of all previous bits and both levels of the binary alphabet are equally likely. The information bits are then error protected by means of a convolutional encoder. After being time and frequency interleaved, the bits are paired into dibits and phase encoded differentially. The OFDM modulation is finally performed by means of an Inverse Fast Fourier Transform (IFFT). After being processed through the mobile channel, the received OFDM signal is first demodulated with an FFT. The information of each subcarrier is then differentially phase decoded and deinterleaved in frequency and in time. The output of the deinterleaver is quantized before being fed to the Viterbi decoder.

FIGURE 38

General model of the DSB system



1.2 Mobile satellite channel mode

The model of the mobile-satellite channel is essentially a Rician fading process which includes a direct path and a Rayleigh fading path with a fading rate that can be set to different values. The spectrum of the Rayleigh process is the classical "U" shape which corresponds to the assumptions of a) uniform distribution of the power of the multipath with arrival angle, and b) the use of an omnidirectional receiving antenna. The direct path can be Doppler-shifted by a constant value to simulate reception in a moving vehicle from different satellite elevation angles. The power of the direct path is assumed constant and the channel K-factor, which is defined as:

$$K = 10 \log \text{(average multipath power/direct path power)}, \qquad (22)$$

can be set to any desired value. In addition to the multipath channel characteristic, additive white Gaussian noise is combined with the signal after the fading process. It must be pointed out that this satellite channel model is frequency non-selective and is valid for narrow-band mobile transmission. Wideband mobile-satellite channel measurements conducted more recently have shown that coherence bandwidth derived from delay spread is about 1 MHz in the worst case in dense urban areas. Such channels would consequently be frequency selective over a bandwidth of 1.5 MHz and would allow the COFDM scheme to provide some improvements through frequency diversity. The results reported here with a flat faded satellite channel model correspond therefore to the worst case situation. Better results are to be expected over frequency selective channels, providing the multipath spread is confined to within the guard interval.

2. Limitations of the simulations

Perfect synchronization and perfect (brick-wall) filtering were assumed in the simulations reported here. Effects of automatic gain control, phase noise in receiver local oscillators as well as non-linearities in transmit or received equipment have not been considered.

3. Simulation results and discussion

The COFDM parameters investigated were the time-interleaving depth, the number of soft decision quantization levels, the constraint length of the convolutional code (which are given in Report ITU-R BS.1203) and the performance of Mode III in mobile-satellite channels for which the results were reported below. In the presentation of these results the energy contained in the guard interval was included in the computation of E_b/N_o. Corresponding carrier-to-noise (C/N) ratios can be easily obtained by subtracting 1 dB from the E_b/N_o values.

3.1 Performance of Mode III in mobile-satellite channels

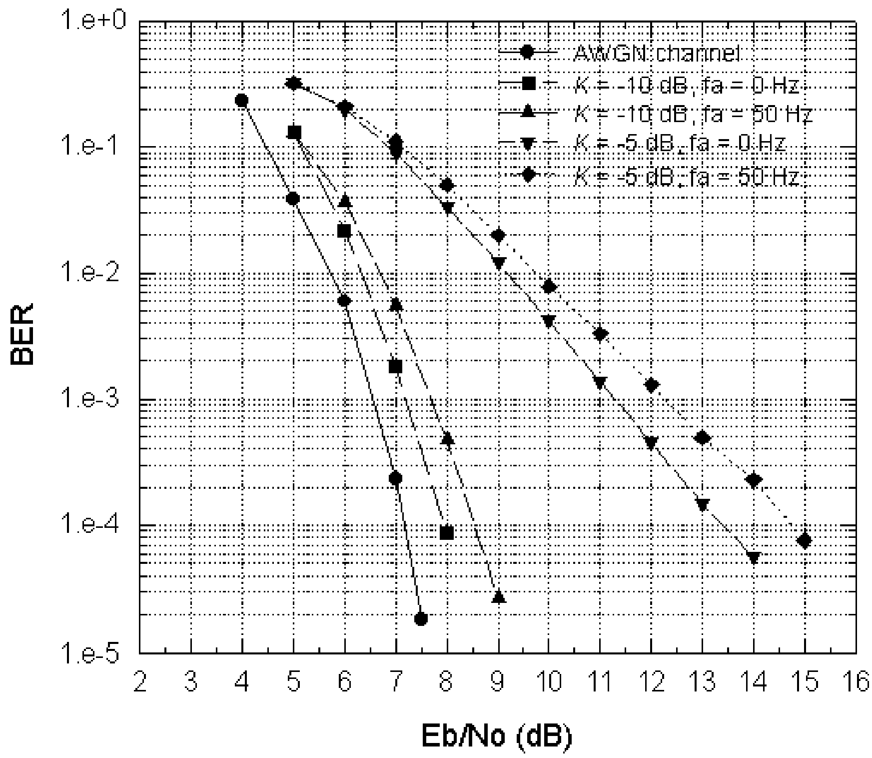
The purpose of this fifth series of simulations was to assess the performance of the Mode III parameters in mobile-satellite channels. The BER versus Eb/No curves were measured in Rician channels with K-factor values of -10 and -5 dB. The vehicle speed was set to 72 km/h so that the maximum Doppler spread associated to the Rayleigh fading was f_{max} = 100 Hz. A Doppler shift (f_a) of 0 Hz (corresponding to a satellite elevation angle of 90°) and 50 Hz (corresponding to a vehicle moving at 72 km/h towards a satellite at an elevation angle of 60°) was applied respectively to the direct path.

The results are shown in Fig. 39. As a reference, the curve in the AWGN channel is shown. With a K-factor of -10 dB, the E_b/N_o value needed to achieve a BER of 10^{-4} was found to be 8 dB for a satellite elevation of 90° and 8.5 dB for an elevation of 60°. These values increase to approximately 13.3 and 14.5 dB respectively when the K-factor is increased to -5 dB.

Additional simulation software is being developed to investigate the effects of hardware implementation factors on the performance of the cofdm scheme.

FIGURE 39

BER as a function of E_b/N_o over satellite mobile channels with different K-factors and different Doppler shifts of the direct path (Mode III, v = 72 km/h)



ANNEX 4

Description of Digital System B

1. Introduction

The Digital Sound Broadcasting System B is a flexible, bandwidth and power-efficient system for providing digital, audio and ancillary digital data broadcasting for reception by indoor/outdoor, fixed and portable, and mobile receivers. System B is designed for satellite as well as terrestrial transmission.

1.1. System status

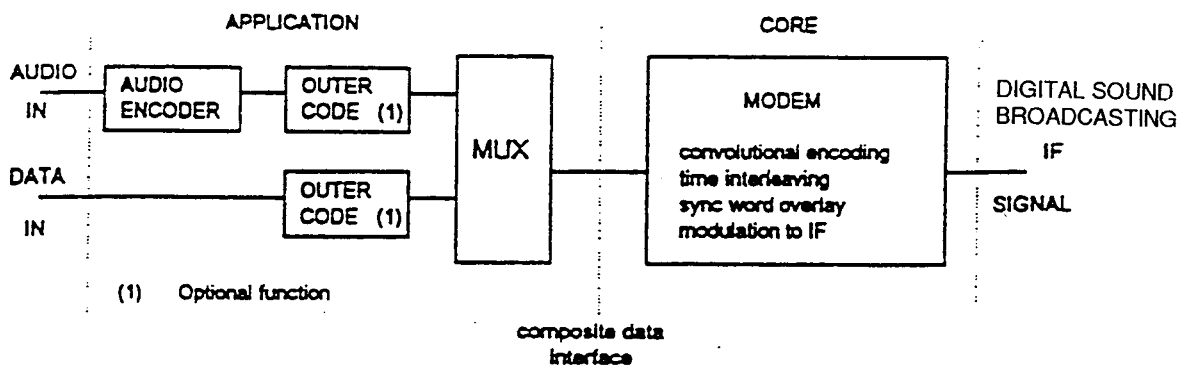
A complete implementation of System B, including the appropriate satellite and terrestrial propagation channel models, exists as a COMDISCO SPW simulation on a Sun work station. An engineering model of the system is currently being built. It will be tested in late 1993 and early 1994 under the auspices of the Electronic Industries Association (EIA), both in the laboratory and via satellite (NASA's Tracking and Data Relay Satellite (TDRS)) under a variety of reception conditions. (See Doc. 10-11S/140 for measurement procedures, Doc. 10-11S/139 for selected system performance characteristics, and Docs. 10-11S/141 and 10-11S/153 for additional information on proposed S-band satellites and testing procedures.)

1.2 System overview

System B is structured into two functional elements, a digital data transport core function (transmitter/receiver/modem), and a data manipulation (audio-compression/data multiplexing) function. This functional division is illustrated by the block diagram of the transmitter in Fig. 40.

FIGURE 40

Transmitter block diagram



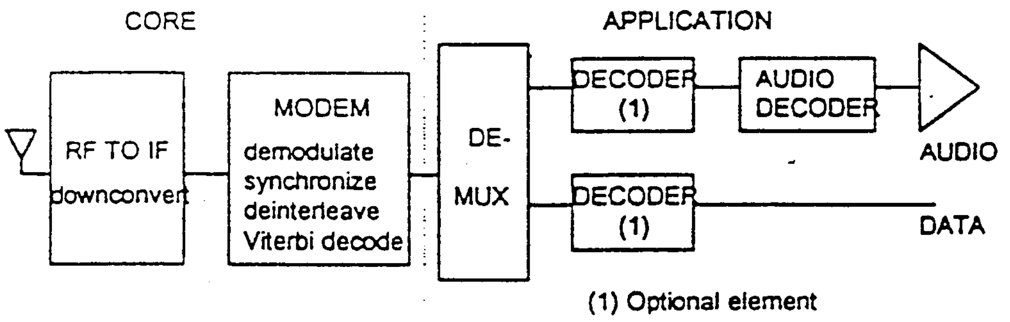
Each System B link is designed to operate over a range of data rates from 32 kbps to 384 kbps. This enables a service provider independent access to a satellite transponder and allows each provider to supply a mix of one or more audio and data channels. It also allows each provider to use the power and bandwidth resources of the transmitter in proportion to each provider's aggregate data rate.

A specific audio-compression scheme for System B is not currently specified. Any scheme which falls within the systems' data rate capabilities can be accommodated. Several audio-compression schemes will be tested during the system testing process and recommendations for each type of service will be made on the basis of audio quality, and required data rate.

The functional division of System B at the receive side is shown in Fig. 41. The receiver is designed to operate over a range of link data rates allowed by the transmission channel. This structure enables access to a given provider's services throughdemultiplexing of a single data stream, and access to other providers by tuning to another frequency channel.

FIGURE 41

Receiver block diagram



The signal structure of System B allows a simple basic digital receiver implementation which will work well in a majority of reception environments. Additional signal-processing functions, which can be added to the basic receiver without impact to the signal structure, have been developed to enhance operation in more difficult reception environments.

2. Signal structure

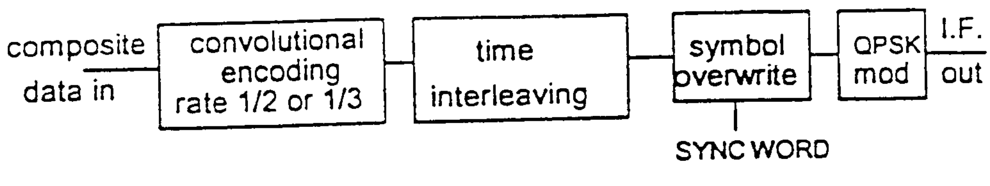
The signal structure of the core system consists of convolutional encoding, followed by time-interleaving, and QPSK modulation with pulse shaping for bandwidth efficiency. An outer code such as a Reed-Solomon code can be added to the data stream of any of the data sources.

3. Signal generation

The steps in the signal construction process are shown in the block diagram of Fig. 42.

FIGURE 42

Signal construction (transmit modem functions)



3.1 Synchronization

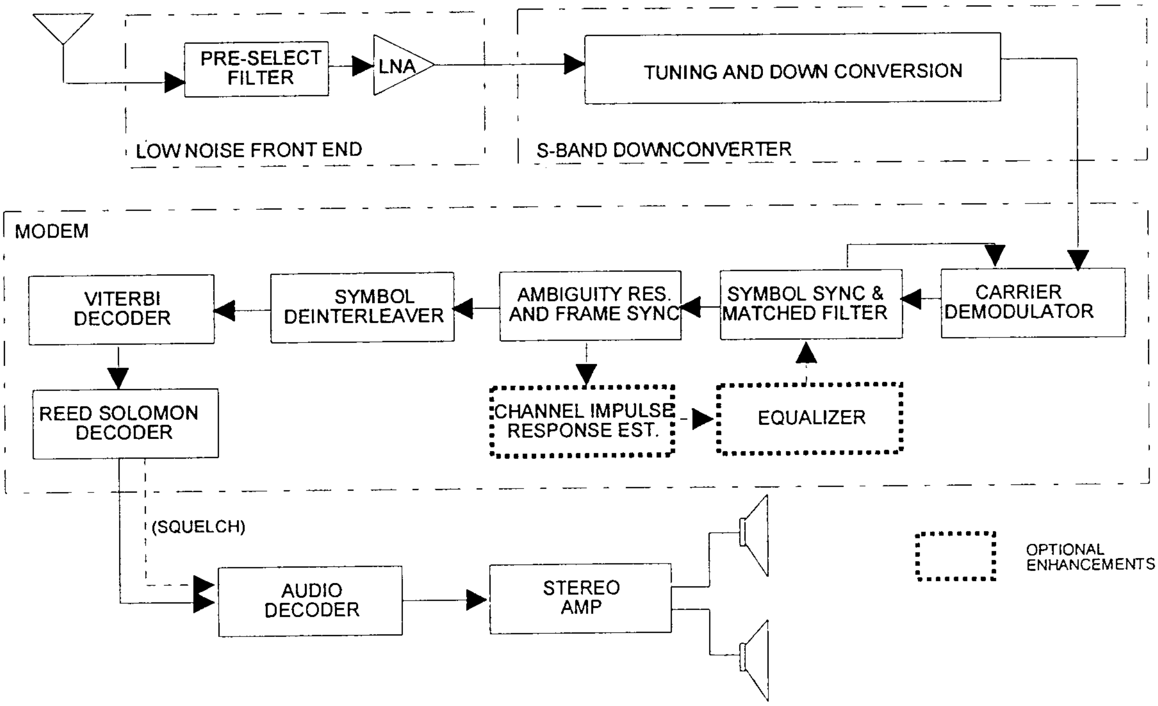
In order to resolve the QPSK ambiguity at the receiver and establish interleaver frame synchronization, a unique sync word is overwritten over part of the symbol stream prior to modulation.

4. Receiver structure

A functional block diagram of the receiver is shown in Fig. 43. Each of its functional blocks is described below.

FIGURE 43

Receiver block diagram



4.1 Core receiver

The core receiver consists of the RF to IF converter and demodulator/detector blocks of Fig. 43. The first block performs the functions of tuning the receiver to the proper RF frequency and converting the received signal down to a low IF frequency. The second block will in most cases be a completely digital implementation. Here the low IF output of the first block is sampled and processed to demodulate, detect, and decode the combined data stream.

4.1.1 Carrier and symbol synchronization loops

Carrier demodulation and data detection takes place in cross-coupled QPSK carrier and bit sync tracking loops. The carrier loop would in most cases be implemented as a Costas loop. Another option to implement carrier modulation is using a block phase estimator, which gives somewhat worse performance than a coherent demodulator, but may be useful in a rapid fading environment.

The symbol synchronization loop is a transition tracking loop which is used to establish symbol timing for all subsequent operations.

4.1.2 Symbol deinterleaving and ambiguity resolution

Detected symbols, in soft decision format, are fed into the time deinterleaver where their original time sequence is re-established. The symbols at the input to the deinterleaver are also correlated against a replica of the sync word which was overlaid on the symbol stream. Detection of the sync word or its inverse allows the establishment of deinterleaver frame sync as well as the resolution of the QPSK ambiguity.

4.1.3 Viterbi decoding

Viterbi decoding of the convolutional code takes place at either the 1/2 or 1/3 rate as chosen by the service provider. Integrated circuits which run at both rates are available so providing both rates is not a significant cost impact to the receiver. The choice of a rate 1/3 code does result in a bandwidth penalty which the service provider may want to absorb, especially if the service is intended for mobile reception in the presence of heavy shadowing.

4.2 Receiver enhancements

Several signal processing enhancements have been developed to improve receiver operation in difficult reception environments.

4.2.1 Channel state-aided decoding

A Viterbi decoder will provide better average performance under fading signal conditions if its input can be assigned a zero weight during the time the signal is below threshold. This can be accomplished by doing a signal-to-noise estimation to detect when a fade occurs.

4.2.2 Antenna diversity

Indoor propagation measurements have shown that large standing waves can occur inside buildings. The peaks and troughs of these waves are fractions of a wavelength apart, so that close spaced antenna diversity is practical. There may be applications for antenna diversity for outdoor, especially mobile reception, conditions as well. The simplest approach is to switch to the other antenna when a signal drop is detected. Depending on conditions, there are probably more complex strategies that can be developed.

4.2.3 Equalization

Equalization is most useful when a signal is distorted by echoes from reflections. In most satellite applications, with reasonable satellite elevation angles, reflected signals are many dB below the direct signal. The problem of echoes is much more severe in terrestrial broadcasting, where several can be close in power to the direct signal. The function of the equalizer is to sort out the competing signals, select the strongest one, and eliminate the effects of the others.

4.3 Application function implementation

This portion of the receiving system consists of the data demultiplexing, optional outer code decoding, and audio-decoding functions. In some applications the use of an outer code is not necessary, or, as in the case with some audio-compression systems, additional error protection is provided within the encoder/decoder circuitry.