Digital Audio Broadcasting ®

Service planning for terrestrial Digital Audio Broadcasting

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As DAB system developers in the Eureka 147 consortium and the EBU move towards the establishment of a complete system specification, and as broadcasters express increasing interest in opening DAB services as soon as 1995, the question of service planning gains in importance. This progress report on service planning studies for DAB single frequency networks (SFN) contains valuable preliminary data concerning required field–strengths and protection ratios for terrestrial DAB services (including protection to and from other broadcast systems such as television and FM radio).

DAB SFNs offer greatest spectrum efficiency if they use many closely–spaced low–power transmitters. However the first terrestrial DAB services will most probably be incorporated within the existing broadcast transmitting– station infrastructure and the article presents the results of coverage predictions for practical DAB SFNs serving large regions from existing transmitter sites.

Further work is required on many aspects of DAB service planning, to refine the prediction models used and ensure that the launch of DAB programme services is not compromised by inadequate coverage.

1. Introduction

Since the early 1950s the pilot–tone frequency modulated (FM) stereo system has been widely used to transmit high–quality radio programmes to the listener

When the stereo FM system was first introduced, the intention was to serve a population who would receive the transmissions with a static receiver fed by a receiving antenna of modest gain and directivity This antenna was to be situated at a height of 10 metres above ground level

The network planning standards agreed for the implementation of the FM system were in accordance with those intentions, and as a result the networks in various countries were planned to serve static domestic installations with good quality reception

More recently, technological developments have led to the manufacture of cheaper mobile and portable FM receivers and as a consequence of this new–found freedom the principal target audience has changed from listeners using static home–based installations to those using mobile and portable receivers The existing FM networks are, of course, able to serve some of these mobile listeners but in many areas reception is impaired by multipath interference and selective fading This is due to the fact that the mobile antenna is necessarily

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The DAB logo has been registered by a member of the Eureka 147 – DAB consortium omnidirectional (so it cannot reject reflected signals) and is generally at a low height. There are millions of mobile receivers currently in use in Europe and this fact alone dictates that a method of serving this vast number of potential customers with a high–quality radio service should be pursued. A successful digital system can be expected to stimulate the European market economy, particularly if a world–wide digital audio broadcasting (DAB) standard is agreed.

With the advent of digital technology the general public now expects the same quality of reception on their radio as they achieve with their home–based digital reproduction equipment such as their compact disc (CD) player.

Digital signals, as such, are not generally suited to broadcast transmission because multipath interference and selective fading render the transmission channel unusable in many cases. In order to overcome these transmission channel problems a European initiative has been taken under the auspices of a project group named "Eureka 147", in conjunction with the European Broadcasting Union (EBU), in order to devise a digital audio broadcasting (DAB) system able to cope with the problems associated with digital transmission in a mobile environment.

The COFDM system (coded orthogonal frequency division multiplex), which is the first digital broadcasting system capable of operating successfully in a multipath and fading environment, has been devised by the Eureka 147 project group. COFDM is a complex system, using frequency division multiplexing with time interleaving in the radio–frequency domain. It is used with an audio sub–band coding system known as MUSICAM which achieves a high–level of bit–rate reduction on the programme source material. The COFDM system has been successfully demonstrated widely in Europe and North America and a European standard is being finalised. Although the signal processing is complex, with present day VLSI technology, receivers can be manufactured at relatively low cost.

This article briefly describes the DAB system, discusses protection ratios and presents the results of some initial planning exercises for single–frequency networks.

2. Description of the DAB system

Recent developments in audio sub–band coding (MUSICAM) have led to bit–rate reduction factors of up to seven times; this means that a stereo programme of near CD quality can be reproduced from a bit–stream of approximately 200 kbit/s, whereas a conventional CD uses 1411 kbit/s.

The coding process [1] relies on the psycho–acoustical characteristics of the human ear which masks low level sounds in the presence of higher levels at similar frequencies. In the example

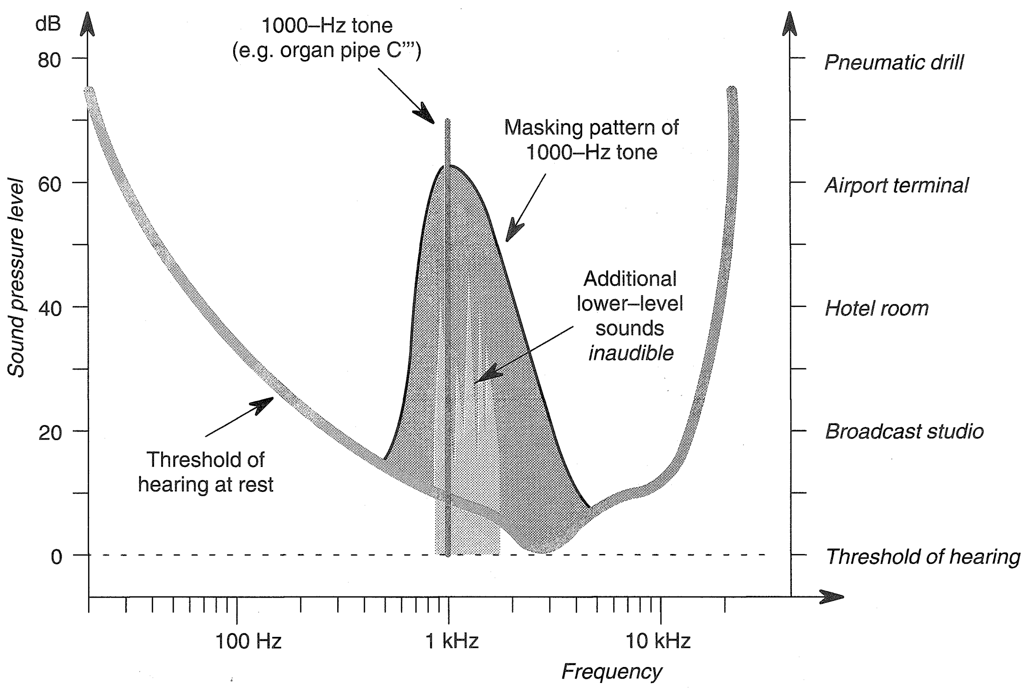


Fig. 1
The psycho–acoustic process of masking (Source SWF)

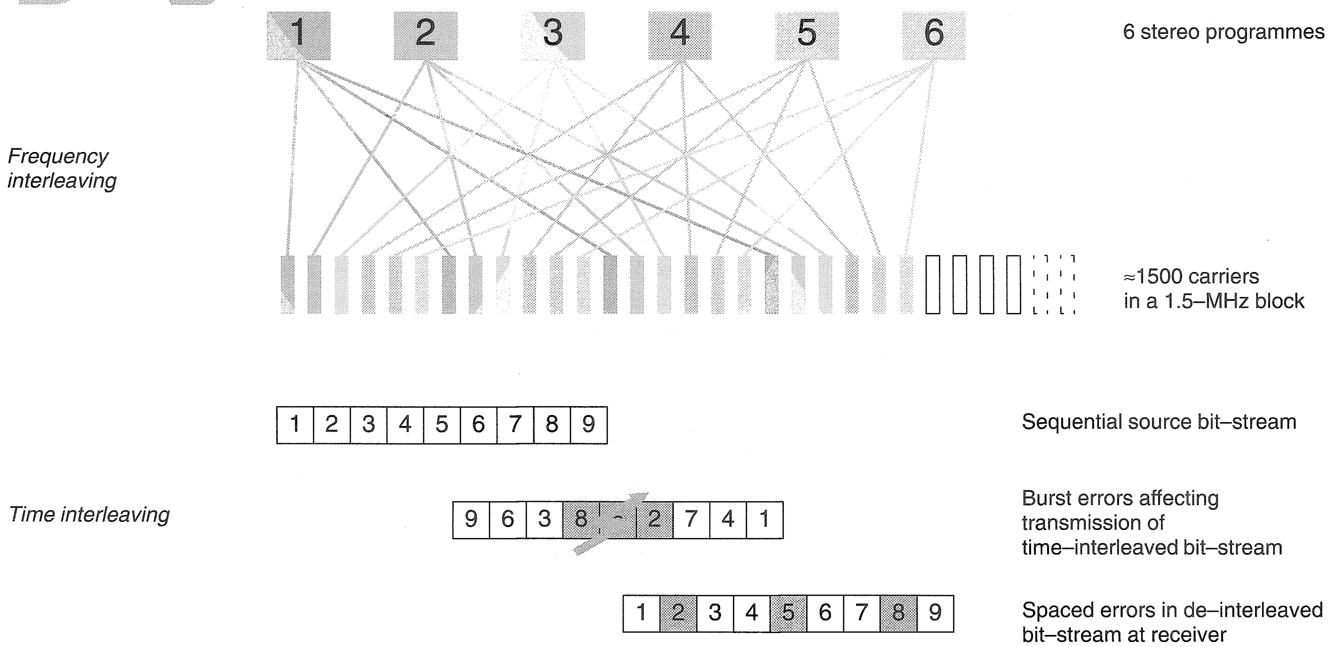


Fig. 2
Distribution of data for six stereo programmes in a 1.5–MHz block bandwidth (Source SWF)

shown in *Fig. 1* the listener would not perceive the audio signals such as those shown in blue lying within the pink area; this means that they need not be digitised and transmitted, thus reducing the amount of data required to describe the composite sound.

In the Eureka 147 system the source coding meets the ISO–MPEG 11172–3 Layer II specification. This is extremely flexible and can be configured to suit the broadcasters' needs since the receiver will readily adapt to the different bit rates.

The other important aspect of the Eureka 147 DAB system is the COFDM transmission technique [2]. The basic principle involves dividing the data from the coder between a large number of adjacent carriers. By ensuring that the symbol duration is longer than the delay spread of the channel, and that a temporal guard interval is left between successive symbols, the system overcomes the problems associated with multipath and selective fading in a Rayleigh channel.

Fig. 2 shows how time and frequency interleaving are obtained. Time interleaving has the effect of making the errors introduced on sequential samples become more evenly spread during the process of de–interleaving in the receiver, thereby allowing better error protection. By spreading the information over a large bandwidth (frequency interleaving), the inter–symbol interference is reduced. A powerful coding technique and sophisticated error–correction algorithms make the Eureka 147 system ideal for providing radio services to mobile, portable and fixed receivers in all types of environment.

The Eureka DAB system has three modes of operation, shown in *Table 1.* Mode I offers the greatest spectrum efficiency and is therefore suitable for terrestrial single frequency networks [3] whilst mode II is preferable for local DAB and mode III for satellites services. A description of the single frequency network (SFN) system using mode I is given in *Section 5.*

Table 1
Principal characteristics of the three COFDM modes

Parameters	COFDM modes		
	Mode I (for SFN)	**Mode II** (for local)	**Mode III** (for satellite)
T_{symbol} (total)	1.25 ms	312.5 µs	156.25 µs
T_{symbol} (useful)	1 ms	250 µs	125 µs
Guard interval	250 µs	62.5 µs	31.25 µs
Maximum delay	300 µs	75 µs	37.5 µs
Maximum frequency*	340 MHz	1.38 GHz	2.76 GHz

* Noise degradation in the most critical case, at maximum frequency, equal to 1 dB at 100 km/h or 4 dB at 200 km/h.

3. Planning criteria

It is envisaged that spectrum for DAB is most likely to be found within the frequency bands already allocated to the broadcast services on a primary or shared basis. Such services are most likely to be television or FM radio but in cases where bands are shared or adjacent, the implications of the introduction of DAB on the fixed, mobile or aeronautical services will also need to be considered. To determine sharing possibilities in a quantitative manner, it is necessary to establish appropriate minimum values of wanted–to–interfering signal levels for the following sharing situations:

- DAB to DAB with the same programmes*
- DAB to DAB with different programmes
- DAB to FM Radio and vice–versa, with RDS/ stereo and mono
- DAB to television (PAL, SECAM and NTSC), and vice–versa**
- DAB to fixed and mobile service systems and vice–versa, including ILS and VOR.

* The "Single Frequency Network" (SFN).

** With their various combinations of NICAM digital sound, teletext and dual FM sound.

Tests to determine appropriate protection ratio values for planning purposes have been carried out by a number of broadcasting research establishments including the BBC, CCETT, TDF, IRT, and YLE [4]. Most of the available data was obtained over the period 1989–1990 when the only available DAB hardware was prototype COFDM equipment working with a bandwidth of 7 MHz.

This prototype equipment fed 15 of the 16 stereo programme channels with sine–sweep data, identical to that used in the "channel–sounding" symbol in each frame. The resultant spectral energy distribution of the COFDM signal in this arrangement has more energy in the higher frequencies of the COFDM signal than would be the case if all the channels were fed with normal programme material. Recognizing this, and also because it enabled comparisons to be made for DAB configurations with reduced bandwidth, most of the investigations of protection ratio for interference to television simulate the DAB signal by bandwidth–limited white noise. These provisional results are sufficient to enable preliminary estimates to be made of sharing possibilities with other broadcast services and for network planning.

In the case of interference to and from television (and of course interference between DAB transmissions) the wanted and interfering services have wide bandwidths and it is usual, in determining protection ratios, to refer to the total DAB power. In the case of interference to and from FM radio, the FM signal bandwidth is smaller than that of the DAB signal. Here it is sometimes convenient to relate the protection ratio to the DAB power within the bandwidth of the FM signal. Care has to be taken to identify the reference condition.

For an interfering FM signal with low deviation, (or a carrier–wave interfering signal) the protection ratio is dependent on the relationship between the wanted and interfering carrier frequencies.

4. Subjective effects of interference

4.1. Interference to television and FM radio

A characteristic of analogue modulation systems such as television and radio is that they exhibit a gradual degradation of quality as the level of interference increases. This is not so with digital systems.

When determining protection ratios for interference from DAB signals to television and FM radio, it is desirable for the accepted limits of impairment to be consistent with those for interference from other television or FM transmissions. It is sometimes difficult to define such reference interference conditions so it is to be expected that there will be some differences between the protection ratio results for interference from DAB given by different organizations. To minimise such variations, common measurement methods and international planning standards should be agreed by the broadcasters.

4.2. Interference to DAB signals

In respect of their tolerance to noise and other interfering signals there are inherent differences between digital and analogue systems. Generally, lower values of C/N ratio and C/I ratio are possible for digital signals, and this has several implications with regard to service planning. First, it is easier to define the required minimum C/N and C/I ratios since there is only a small difference in levels between the ratios for "just perceptible" interference and loss of intelligibility; consequently, the effect of wanted programme content on required protection ratios is reduced. Also, because of the rapid transition from high quality to complete loss of signal, the service must be planned to achieve satisfactory C/N and C/I ratios for a higher percentage of time and locations than is usual for analogue modulations; a suitable value might be, say, 99%.

Television and FM coverage is usually defined in terms of a field strength at the fringe of the service area. The coverage is reduced by the presence of areas where the wanted service is not protected to an agreed degree against interference from other transmitters. The limits with respect to noise and interference can be considered independently. In the case of a DAB service the subjective effects of noise and interference from another DAB transmission are virtually identical and the overall coverage limit is set by the combined effect of noise and interference (C/N+I ratio). Therefore if such a service is to be planned to operate down to low values of C/I ratio, close to the theoretical limit, then it is necessary to maintain a relatively high degree of protection against noise (C/N ratio). It is likely that coverages will be assessed in terms of protection margin rather than field strength.

4.3. Protection ratios for DAB services

The values discussed in this article are provisional. More definitive values will become available as a result of detailed subjective tests using the 1.5 MHz DAB block bandwidth recently agreed by the Eureka project.

In the following discussion, the protection ratios are expressed in terms of the total radiated power of the DAB system. Unless otherwise specified (i.e. if noise was used) the COFDM system utilised in these initial tests had a bit rate of 168 kbit/s per mono channel, a capacity of 33 mono channels and an overall bandwidth of 7 MHz.

4.3.1. Protection between DAB services

The effect of interference from an uncorrelated co–channel DAB transmission is similar to that of noise. The precise value of minimum signal–to–noise ratio will depend on the amount of error protection used in the system but is likely to be slightly below 10 dB. If a DAB network is to be planned in such a way that the service is limited by interference from other transmissions, then it follows that the limiting C/N ratio should be about 15 dB. This same value would be required for the minimum C/I ratio in a noise–limited service. In common with other digital systems, the minimum threshold level for the C/I and C/N ratios is critical, in view of the rapid transition from an unimpaired signal to complete failure over a ratio change of only 1 to 2 dB [1]. Continuous interference by multiple uncorrelated DAB transmissions can readily be assessed by the power sum method (PSM).

4.3.2. Protection of DAB against CW and FM transmissions

A carrier–wave (CW) signal may be regarded as a limiting condition of an FM transmission. For CW interference the protection ratio depends on the frequency separation from the DAB signal carriers. The most favourable condition occurs when carriers are coincident, the least favourable occurs with the CW signal mid–way between DAB carriers. Results obtained by the CCETT and BBC are indicated in *Table 2*. In these tests the FM transmission carried coloured noise modulation according to CCIR Recommendations 641 and 559. The impairment threshold to which the protection ratios refer was measured objectively and corresponds to a bit–error–rate (BER) of 10^{-3}.

Broadcasters currently tend to operate their FM transmitters at high mean deviations so it may be appropriate to assume a protection ratio no lower than 1 dB for interference from FM. Further work is required to determine the effect of multiple FM transmissions on a DAB service, but the limiting condition for this situation will be that of white noise, correspoding to a protection ratio of 10 dB.

4.3.3. Protection of FM services against interference from DAB

Subjective assessments have been carried out by the BBC to determine the interference to stereo FM programmes by wide–band white noise. The tests involved sixteen listeners and nine different receivers. For fairly critical music programme content, 50% of listeners judged interference as "just

Table 2
Protection ratios (in dB) for DAB services against interference from CW and FM transmissions

Results from	CW (Coincident with DAB carriers)	CW (Mid–way between DAB carriers)	FM
CCETT	–12	–4	0
BBC	–10	–0.5	1.5

perceptible" (corresponding to grade 4.5 in the 5–point CCIR quality scale), at a protection ratio of 40 dB (referred to the noise power in a bandwidth of 7 MHz).

To refer this protection ratio to the equivalent noise power in an FM receiver bandwidth of 150 kHz, the value requires to be increased by 16.7 dB, giving a total of 56.7 dB. The corresponding co–channel protection ratio given in CCIR Recommendation 412 for FM interference to stereo is only 45 dB.

To investigate this apparent anomaly, further tests were carried out by the BBC, including tests using the original 7 MHz COFDM equipment as the interfering source. These tests indicated that:

- The criterion of "just perceptible on critical programme" corresponded to a demodulated audio signal–to–noise ratio of 66 dB, as compared with the value of 50 dB for which the protection ratios of Recommendation 412 are considered to apply.
- The protection ratio for an interfering COFDM signal was some 6 dB lower than for white noise for a stereo wanted signal. The corresponding difference for a wanted mono signal was only 1 dB.
- For COFDM interference, the protection ratio required for a stereo service is 36 dB; this value is some 15 dB higher than for mono which requires a protection ratio of the order of 21 dB. This is a much greater difference than that indicated in CCIR Recommendation 412 for FM interference. Further work is required to confirm the values of protection ratio using a 1.5 MHz bandwidth COFDM signal carrying normal programme signals on all channels; such tests should examine closely the extent of any variations which may be dependent on the precise frequency difference between the stereo subcarriers. The values above refer to the total power in a 7 MHz DAB system.

This investigation emphasises the importance of ensuring that protection ratios derived for DAB services correspond to the same impairment standards as are used for current FM and television planning.

4.4. *Compatibility with television*

4.4.1 . *Protection ratios for interference to television transmissions from DAB*

a) Interference to PAL television

Tests have been carried out by IRT to assess protection ratios for interference to PAL television using white noise of various bandwidths to simulate interference from DAB. Protection ratios derived from the IRT results are given in *Fig. 3a* for subjective impairments considered equivalent to those in CCIR Recommendation 655 for interference from other television transmissions. Tests by the BBC covered a wider range of frequency separations. The relative protection ratios from the BBC tests, referenced to the IRT protection ratios, give the additional results indicated in *Fig. 3b*.

b) DAB interference to SECAM and M/NTSC television

Tests were carried out by YLE to determine protection ratios for interference to the SECAM system. The DAB signal was simulated by noise with a bandwidth of 6 MHz, assumed to fully overlap the video spectrum. Six observers made separate

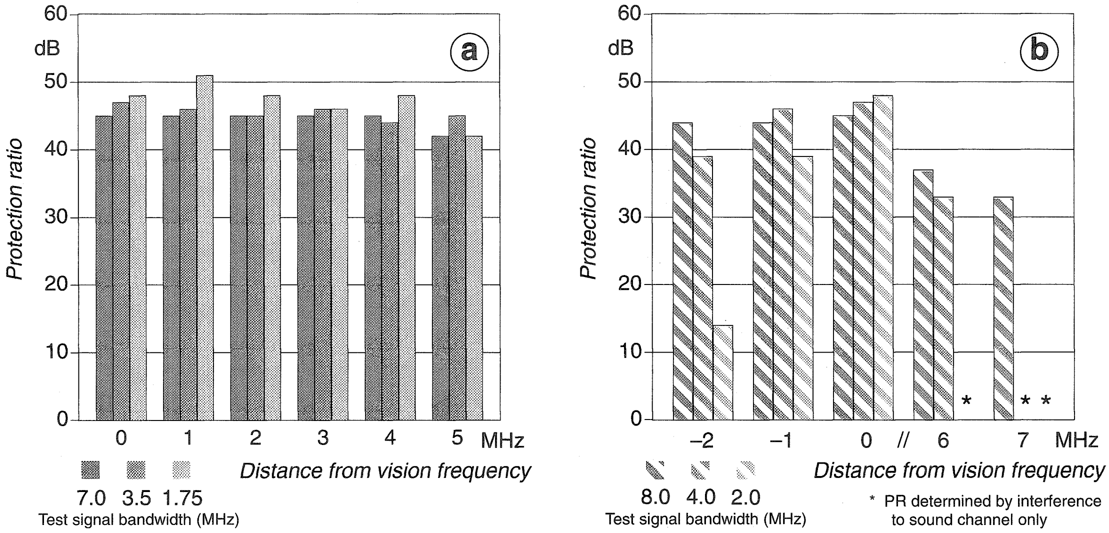


Fig. 3
Protection ratios for PAL television from DAB

a) IRT tests

b) BBC tests

(Noise test signals in both cases)

Table 3
Adjacent–channel protection ratio for "just perceptible" interference

Channel seperation (MHz)	Interference relative to wanted signal	
	Wanted = –35 dBm	Wanted = –55 dBm
+1	–12.75	–21.75
–1	–7.75	–9.5

(mean for four receivers)

assessments of the protection ratios at the limit of perceptibility. The protection ratio obtained in this way was 52 dB, which is identical to that obtained by the IRT for PAL. Tests on a second receiver indicated a required protection ratio some 2 dB lower. Protection ratios measured by TDF give similar results.

Tests have been carried out in Canada [5] to assess the co–channel protection ratio for interference to M/NTSC television, with the prototype 7 MHz COFDM equipment as the source of the interfering signal. For "just perceptible" interference the required protection ratio was 42 dB; this is some 10 dB lower than the value for "limit of perceptibility" obtained by IRT (for the PAL system), but very similar to those of the BBC. In view of this fact and the IRT measurements, a compromise protection ratio value for COFDM interferences to television would appear to be in the order of 46 dB. The Canadian tests were extended to examine the case where the COFDM signal was offset by integer numbers of television channels from the wanted television signal. The results for the two adjacent channels are indicated in *Table 3* for two levels of wanted signal.

For greater channel separations the protection ratios were all more negative than –15 dB and –23 dB for wanted signals of –35 dBm and –55 dBm respectively. The Canadian test report stresses that the results are provisional because the COFDM system was not operating with real audio signals on all channels.

4.4.2. *Protection ratios for interference to DAB from PAL and SECAM television*

The required protection ratios will depend very much on the overall bandwidth of the DAB system and its position within the television channel. However the interfering television signal will take one of the following forms:

i) Vision carrier only within DAB bandwidth.

ii) Sound carrier only within DAB bandwidth.

iii) Both vision and sound carriers within DAB bandwidth (for 625–line television systems this possibility implies a DAB bandwidth of at least 5.5 MHz), which is unlikely in practice following the Eureka decision favouring a 1.5 MHz block bandwidth, unless multiple 1.5 MHz blocks are transmitted together.

iv) Neither vision nor sound frequencies within DAB bandwidth.

In most cases there will be an interference contribution due to energy contained in the vision sidebands, and it may be convenient to consider this first. Effectively this can be considered as equivalent to noise requiring a protection ratio of 10 dB (referenced to the total sideband power within the DAB spectrum). This sideband power is unlikely to exceed a level of –20 dB relative to the vision carrier. Hence if the protection ratio is referenced to the vision carrier power, the highest value is likely to be –10 dB.

Considering now the effects of the vision and sound carriers: for (i) and (ii) the relevant protection ratios are those indicated in *Table 2*, bearing in mind that the maximum deviation of the television sound signal is somewhat lower than for pilot–tone FM radio. Noting however, the general use of a 10 dB vision/sound power ratio for PAL television, it follows that with television powers referenced to the vision carrier, the effective protection ratio for the sound carrier falls between those for the two relative frequency conditions for the CW vision carrier. For (iii) the overall protection ratio will result from the combined effect of the two individual carriers, which are likely to have comparable interference potential provided the vision carrier frequency is not close to the worst–case condition mid–way between DAB carriers. In general, therefore, it would appear that the interference potential of either vision or sound carriers alone will be somewhat greater than for the power contained in the vision sidebands and there should therefore be some planning advantage for protection of DAB services if these can be positioned in order to avoid television carriers in a shared band.

The Canadian tests [5] examined the effect of co–channel interference from M/NTSC television to a 7 MHz COFDM transmission. Protection ratios for "just perceptible" interference range from –9 dB to –4 dB as the wanted signal level reduces from –40 dBm to –80 dBm. Further developments within the Eureka 147/EBU consortium, resulting in an agreed block bandwidth of 1.5 MHz mean that the work undertaken to date must be regarded as preliminary and further work using the revised bandwidth is necessary.

Tests undertaken by the BBC [6] suggest that if the bandwidth of a digital signal is reduced to about

1.5 MHz the television protection ratio will become worse and tend to shift towards the limiting CW case, but these results must be treated with caution since they relate to a single–carrier 2 Mbits/s QPSK signal. However, the figures given here have been judged sufficiently reliable to allow some preliminary frequency planning exercises to start within the broadcast bands.

4.4.3. Protection ratios between DAB and the aeronautical and mobile services

Little or no work on protection ratios related to mobile services has been undertaken at the time of writing. If DAB is to share, or be adjacent to, mobile bands then the appropriate protection ratios must be established. This is especially important for land mobile services adjacent to Band II and the aeronautical mobile services above 230 MHz which are adjacent to the upper block in channel 12.

The aeronautical radionavigation services (ILS and VOR) are vulnerable to interference from FM services in Band II, so it is essential that these services should be protected if DAB is to use this band. A preliminary analysis by the IRT [7] shows that, with the high number of carriers in the COFDM system, the probability that intermodulation products from DAB services in the upper part of Band II will fall in the aeronautical radionavigation band above 108 MHz is high. In addition, the intermodulation noise floor of an amplified DAB signal can cause A1 interference to ILS and VOR services. This topic is still under discussion in the CCIR and no figures for protection are yet available.

4.5. Minimum field–strength requirements

Certain assumptions must be made before the powers required to achieve necessary minimum signal–to–noise levels can be determined:

i) Noise bandwidth/stereo programme: A value of 300 kHz is chosen as a compromise within the range considered by Eureka 147.

ii) Frequency: Enquiries carried out within the EBU have indicated that a majority of members favour the use of part of Band III. Accordingly, 200 MHz is assumed as a representative frequency.

iii) Receiver noise factor: Whilst recognizing that much lower values of noise factor are achievable, it is considered that for mass manufactured equipment a value of between 6 and 10 dB is likely. A value of 8 dB is assumed (corresponding to an equivalent noise temperature of about 2000 K).

Taking the classic formula relating noise power to bandwidth and noise factor:

$$P_N = kTB$$

where P_N = noise power
k = Boltzmann's constant
T = equivalent noise temperature
B = noise bandwidth

and substituting the values from (i) and (iii), we obtain:

Effective receiver noise power

$$= 1.38 \times 10^{-23} \times 2000 \times 3 \times 10^{5}$$

$$= 8.28 \times 10^{-15}\ \text{W}$$

corresponding to a terminated input voltage of:

$$0.76 \times 10^{-6}\ \text{V}$$

$$= -2.4\ \text{dB}\mu\text{V (into } 70\ \Omega)$$

To achieve a signal–to–noise ratio of 10 dB the required e.m.f. = –2.4 + 10 + 6 = 13.6 dBμV

For mobile reception it may be assumed that the receiving antenna will be a whip with an effective gain of, say, –2 dB relative to a dipole. At 200 MHz the effective length of a half–wave dipole is –6.4 dB relative to 1 m. Hence an e.m.f. of 13.6 dBμV corresponds to a field–strength of 13.6 + 2 + 6.4 = 22 dB(μV/m)

This will be the required field strength per programme at the car receiving antenna. To enable the propagation model of CCIR Recommendation 370 to be used it is more convenient to refer to a receiving antenna height of 10 m. An analysis of a substantial number of height–gain measurements at VHF in suburban and urban areas [8] indicates a median value of 12 dB. Other (unpublished) measurements carried out by the BBC at 141 MHz in the London area indicate that mean receiving antenna height gains reduce with an increase in building density from 14 dB in rural areas to 4 dB in dense urban areas. The low values in urban areas tend to result from the depression of field–strengths at 10 m (implying that the variation of field–strength with clutter density at car antenna heights may be less than at 10 m). Since the propagation model of CCIR Recommendation 370 does not take full account of this "urban depression" of field–strength it is probably appropriate, for our purpose, to assume a height gain value appropriate to rural and suburban areas. A value of 12 dB is assumed, implying an equivalent minimum field–strength at 10 m = 34 dB(μV/m).

Finally there are two further corrections which are less readily quantifiable. The first is a correction for *location variation*, bearing in mind that the value of 34 dB(μV/m) quoted above represents a median (50%) location value. For a mobile analogue service it might be sufficient to plan on the basis of providing the minimum nominal field at 90% locations, recognizing that this would still provide an acceptable quality at a much higher percentage of locations. Such an assumption is not safe for a digital service due to the much more rapid rate of impairment when signal strengths fall below the nominal minimum level. If protection were to be planned for 99% locations, the propagation model of Recommendation 370 requires an allowance of 19 dB. However it seems likely that this can be reduced because of the constructive effects of multipath signals in the case of DAB, and the possibility of reception from more than one uncorrelated transmission. This is an aspect of planning which requires further investigation and the variation of field strength with location in small areas is discussed in [9].

Provisionally an allowance of 12 dB will be assumed, subject to the proviso that no further allowance is made for the constructive addition of signal contributions.

The second correction is to take account of the effects of *man–made noise*. Here it must be assumed that care will have been taken in suppressing potential interference sources on the vehicle containing the receiver. Nevertheless tests carried out by the BBC have indicated that, at a frequency of around 200 MHz, external man–made interference in urban areas can typically raise the noise floor by about 7 dB; this figure will be higher for lower frequencies.

Assuming that transmitters would generally be sited to avoid providing minimum field–strengths in urban areas, a nominal allowance of 4 dB will be taken for this factor in this analysis. (Part of this allowance is also considered to take account of co–channel interference, assuming a C/I ratio of not less than 16 dB).

Adding these allowances for local variation and man–made noise to the value of 34 dB(μV/m) leads to a required median field strength of 50 dB(μV/m). From this figure it is possible, from the 50% time propagation curves of Recommendation 370, to deduce the required effective radiated powers per stereo programme, at 10 metres a.g.l for a car radio service. An additional allowance will be required to ensure adequate coverage to portable receivers in domestic dwellings. A provisional figure of 7 dB is discussed later but this must be verified by additional field trials.

Since the Eureka 147 consortium has decided to adopt a fixed DAB block bandwidth it would be prudent to start thinking about using the power or field–strength required per DAB block rather than that for a single programme. This is important because, as noted earlier, the DAB multiplex is configurable and the number of programmes can change whilst the block bandwidth remains constant. The ratio of 1.5 MHz to 300 kHz implies an additional 7 dB, giving a wanted field–strength level of 57 dB(μV/m) for vehicular reception of a 1.5 MHz block.

5. The single frequency network (SFN)

5.1. Basic SFN principles

A fundamental feature of the COFDM system, discussed in *Section 2*, is the ability to operate satisfactorily in areas having high levels of multipath propagation. This is achieved by incorporating a guard interval in the time domain. Provided the longest multipath delay time does not exceed this guard interval then all signal components received add constructively, effectively on a power sum basis. If the delay times increase to exceed the guard interval the constructive effect of the multipath reflections is reduced and the interference effect increases. The relationship between the constructive and interference signal power contributions as a function of delay relative to the guard interval is discussed in [2].

The effect of the interfering contribution is similar to that of noise, or of interference from another digital transmission carrying different programmes. The value of protection ratio required to avoid interference from such a signal will be of the order of 10 dB and this value will be assumed in the following discussion.

This 10 dB ratio occurs if the multipath delay is about 1.2 x guard interval. From the viewpoint of signal processing within the receiver, a multipath signal is indistinguishable from another, suitably synchronized, transmission carrying the same programmes. Therefore a COFDM network employing a single frequency block can be established with multiple transmitters over an extensive area without mutual interference – providing that the delay times of all signals of significant level do not greatly exceed the guard interval. This is the principle of the single frequency network (SFN).

As stated in *Section 2* the COFDM system has been designed to operate in several modes. Mode I (guard interval 250 μs) covers the needs of a terrestrial SFN service for large national or regional areas and offers the greatest spectrum efficiency. As the size of each individual SFN reduces, (for example, to provide regional networks within individual countries) so the requirement for spectrum increases. We will deal here primarily with national or regional single frequency networks. In the start–up phase of DAB services, a minimum of four frequency blocks will be required in order to permit every country in Europe to initiate a national single frequency network; this will be discussed later.

Within a given regional or national SFN covering, for example, Bavaria or the United Kingdom, frequency blocks allocated to other countries can be re–used provide that agreed protection ratio standards are respected. For example, if Bavaria is allocated block A then blocks C or D could be used, say, in Munich or other cities for local coverage.

In principle, frequencies up to 300 MHz are suitable for Mode I DAB SFNs, however, in view of the severe spectrum congestion in Europe any band (I, II or III) could be considered. Band III is the ideal start–up band with the eventual aim of moving into Band II, but in the interim period receivers should at least be capable of covering Bands I to III.

Programme distribution to a series of SFN transmitters is discussed in [3]. Satellite or terrestrial distribution are two options. With the former method a satellite transponder could supply the multiplexed programmes direct to each transmitter site, obviating the need for terrestrial links together with coders and modulators for each site.

The choice of feed arrangements is complex and will probably be determined by the size of the network and the financial situation of individual broadcasting organizations. Generally, the larger the coverage area and the larger the number of transmitters, the more economic the satellite option becomes; the penalty is the cost of providing a back–up satellite to safeguard against failure of the main programme feed.

5.2. Optimisation of an SFN

The main advantage of DAB SFNs is in respect to the use of frequency spectrum, because coverage can be adapted to the special needs of the broadcasters without requiring additional spectrum. The design of the SFNs has to strike a balance between the coverage requirements (corresponding, ideally, to "everywhere at any time" for mobile, portable and fixed receivers), and the cost of building and operating the network. In addition, the power of the transmitters will depend on the frequency band used for DAB.

For a parking band, to be used for DAB service start–up pending the clearance of channels for more permanent services (e.g. channel 12 in Band III), coordination with countries using other services such as television and mobile is essential. As a general rule, the coordination of new transmitters is much easier if the radiated powers and the effective heights are low.

Theoretical exercises carried out by the BBC indicate that a closely–spaced network of low–powered transmitters is the most efficient solution for DAB network planning, although this may not be the most cost–effective in view of the number of existing transmission sites owned or rented by the broadcasters.

The first practical planning exercises show that good DAB coverage for mobile reception appears to be feasible with levels of transmitter power–per–programme which are low, compared to VHF/FM. For the coverage of larger cities some additional small transmitters will be needed to guarantee service along most of the streets and inside buildings. In areas with deep valleys which cannot be reached by signals from the main transmitters, additional fill–in transmitters will also be required.

Further investigative field trials with SFNs are needed to obtain more experience in their behaviour, in order to adapt propagation models to the new DAB system.

5.3. Overall SFN spectrum requirements

As discussed previously, an SFN can be extended over a semi–infinite area. However at the limit of any such area the protection ratio required between this network and another network carrying a different set of programmes will be about 10 dB. Clearly, therefore, it is not possible to use the same frequency block for different programmes in contiguous areas; nevertheless, if the transmitter powers are reduced close to the periphery of an area, the width of the zone within which frequency block re–use is not possible will also be reduced.

The number of frequency blocks required to produce complete coverages of SFNs is dependent upon the size of the area to be covered by each network. Obviously the frequency block used in any one country could be re–used, for different programmes, over the major part of other countries. With a requirement of a single frequency block for individual countries, a total of three frequency blocks might suffice in many cases. However examples can be identified where this would be inadequate. One such area within Europe is that of Luxembourg. This country has borders with three others (France, Belgium and Germany), all of which have borders with each other. To cater for such circumstances a minimum of four frequency blocks would be required. As the difference in size of each individual SFN increases, with a corresponding reduction in spatial regularity, (e.g. to provide regional networks within individual countries) so the requirement for spectrum increases. In the limit, the number of frequency blocks approaches that required for conventional planning, with each transmitter carrying a different programme set, but in practice it seems likely that about eight blocks would provide a good deal of flexibility in planning.

6. Practical planning examples

6.1 . The Bavarian experience

In common with various other organizations within Europe the Bayerischer Rundfunk (BR) has developed a computer–aided planning system for broadcast coverage predictions. Over the last two years a system known as CATS (computer aided transmitter simulation) with data bases of terrain height, buildings distribution, trees and population density has been developed (see *Fig. 4*). The maximum data base resolution is 100 x 100 metres. Utilising these data bases in conjunction with a workstation it is possible to perform wanted field strength or interference predictions for any site taking into account the relevant protection ratios. Predictions are first made for transmitter e.r.p.s of 1 kW and are then corrected for the required power and antenna pattern. If the network comprises several transmitters, matrix calculations are made in a given service area for all contributing transmitters. CATS offers the service planner a number of options including predictions over a range of frequencies using different propagation models.

6.1.1. DAB aspects

The CATS prediction model is being adapted to the special needs of DAB planning. The main differences, compared to the planning of conventional broadcasting services, are in the single frequency network concept (SFN). This requires a greater percentage of location coverage, uses a lower receiving antenna height, suffers loss of service at a certain C/I ratio and has a different location variation factor due to the constructive additive effect of the multiple wideband transmissions in the SFN. It is intended to adapt the CATS prediction model in an iterative process, making use of the results of the field trials to perfect the system.

6.1.2. Preliminary model for the prediction of the DAB coverage

a) Calculation of the field–strength

The coverage is calculated for a given area with the CATS software tool and a terrain data base with a basic resolution 100 x 100 m. The path profile is calculated to each "pixel", for a receiving antenna height of 2 m. Two cases are considered:

i) If the first fresnel zone is free of obstacles, the field–strength is calculated in accordance with CCIR Recommendation 370–5 with the modification that the actual effective height is calculated for each pixel. The minimum field–strength derived in *Section 4.5.* is taken.

ii) For paths in which the first fresnel zone is disturbed, diffraction at the three main knife edges is calculated in accordance with the Deygout model [10].

The free–space field–strength is reduced by the losses determined from CCIR Report 715–3 for the three knife edges. In addition, a distance–dependant loss is applied, together with a correction for 99% locations.

b) Coverage of the single frequency network

The coverage of a DAB SFN is calculated by adding the signals coming from the different transmitters in the network. As a first step the power sum method (PSM) can be used, since the DAB receiver makes use of all signals inside the guard interval.

If the DAB transmitter network is well designed, it can be assumed that only a few locations will exist where the path difference of the signals from different transmitter sites is greater than, say, 90 km and a signal falling outside the guard interval has a higher field–strength than those within the in-

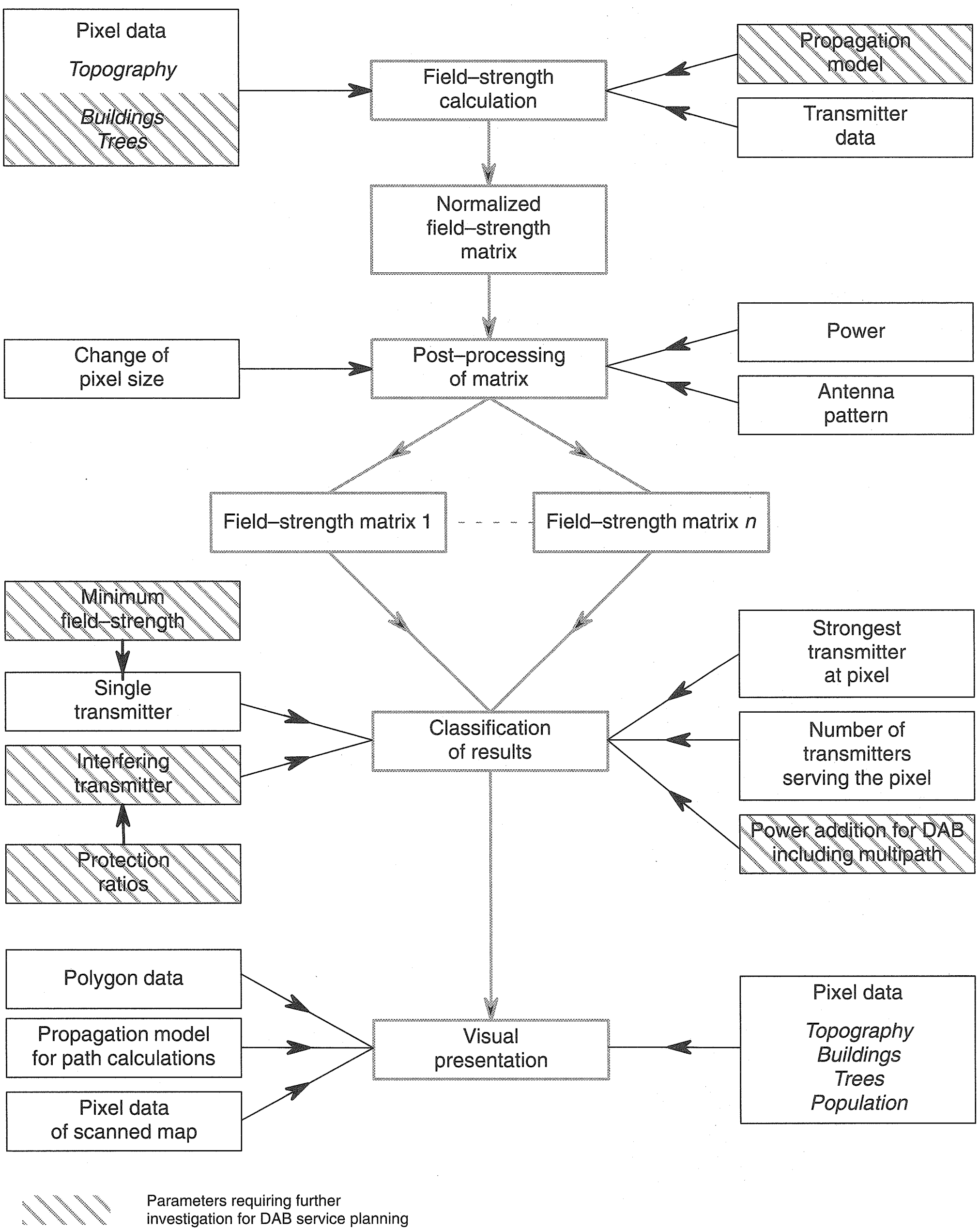


Fig. 4
Computer–aided transmitter simulation (CATS) system used by the Bayerischer Rundfunk for service planning.

terval. The performance of the receiver is critical in this respect, since it must be able to shift its capture window to the strongest DAB signal arriving within the guard interval. Further work is required on this topic, the results of which will be taken into account when refining the prediction model.

6.1.3. *First results of DAB coverage prediction for Bavaria*

A network for a new service such as DAB can be designed in different ways. At the moment there is little practical information on planning DAB SFNs and this makes it difficult to choose the transmission parameters. More field work and planning exercises are needed in order to study the impact of the different variables on coverage and to compare predictions with measurements.

Assuptions made in the Bavarian planning exercises were as follows:

– Block bandwidth (5 or 6 programmes):	1.5 MHz
– Frequency:	225 MHz.
– Required coverage:	99% locations
– Antenna height:	2/3 of existing mast heights

- To allow block re–use, transmitting antennas close to service area boundaries are directional, with a maximum front–to–back ratio of 20 dB.
- No account is taken of interference to or from television, mobile services or other DAB services.
- The e.r.p. given is for a block–bandwith of 1.5 MHz.

Three different network configurations have been studied, all making use of existing transmitting stations operated by the Bayerischer Rundfunk and the Deutsche Bundespost–Telekom.

a) SFN using the VHF/FM transmitter sites of the Bayerischer Rundfunk (BR)

In a first approach (Network 1) all existing transmitter sites of the VHF–FM network of the Bayerische Rundfunk were taken as transmitter sites for a DAB SFN for Bavaria. The e.r.p. for the 1.5 MHz DAB block was as follows:

- 20 transmitters with e.r.p.s of 0.5 to 1.0 kW
- 9 transmitters with an e.r.p.s of 0.02 to 0.05 kW

The results for the coverage prediction with this SFN using the terrain data base and the propogation model described above are shown in *Fig. 5*. The coloured areas (red, green, blue and yellow) show those pixels with a field–strength above the minimum value given in *Section 3*. The different colours indicate the number of transmitters which are expected to serve the pixel (red = 1, green = 2, blue = 3 and yellow = 4).

In *Fig. 6*, the addition of the signals (PSM) from the different transmitters has been taken into account, with the effect that some of the pixels shown as being below the minimum field–strength in *Fig. 5* now achieve the minimum required level.

b) SFN with transmitter sites of the BR and the DBP–Telekom

In *Fig. 6* it can be seen that there are still a number of areas (shaded grey) inside Bavaria which will not be served by DAB in mobile reception conditions where the required percentage location coverage has to be of the order of 99%.

A second network was designed using, in addition, some of the existing main transmitter sites of the DBP–Telekom. This mixed network (26 BR sites and 9 DBP–T sites), referred to as Network 2, comprises:

- 25 transmitters with e.r.p.s of 0.5 to 1.0 kW
- 10 transmitters with e.r.p.s of 0.02 to 0.05 kW.

It can be seen clearly from *Figs 7* and *8* that this network will give much better coverage. The location probability for the coverage will be greater than for Network 1, owing to the fact that there are more pixels with reception from multiple transmitters of the SFN, shown in green and blue in *Fig. 7*.

c) Modified SFN with BR sites but high–power transmitters

In a second approach Network 1, using the BR transmitter sites only, was modified to increase the transmitter powers by some 10 dB as shown below (Network 3):

- 21 transmitters with e.r.p.s of 5.0 to 10.0 kW
- 5 transmitters with e.r.p.s of 0.5 to 4.9 kW
- 3 transmitters with e.r.p.s below 0.5 kW.

This change resulted in greater amounts of overlapping coverage, as seen in *Fig. 9*. The effect of power addition in these areas is not shown in this case since the differences are not significant compared to *Fig. 8* except that some areas outside Bavaria receive greater coverage. It has to be stressed that the use of powers of the order of 10 kW seems to be very unlikely in the channel 12 parking band because of likely difficulties in coordination with television and other services. However, for DAB services in Band II these power levels should be possible.

6.1.4. Statistical comparisons and margins

A quantitive comparison of the three networks has been made by calculating the total coverage area using the power sum method (PSM) to sum all contributing signals, i.e. the green, blue and yellow pixels of *Figs 5, 7* and *9*. The results are indicated in *Table 4a)* which gives the total coverage area and percentage covered, relative to the results for the 10–kW situation of Network 3 which covers some 79200 km^2. Figures without the use of the power sum method are also given. By applying the PSM an apparent coverage gain between 4% and 10% is obtained. With the greater overlap (pixels served by multiple transmitters), Network 3 will provide greater percentage location coverage and hence a better service to mobile and portable receivers.

In the planning examples shown so far, no account has been taken of the fact that the frequency block re–use factor is higher if networks are planned with a margin allowance for interference from other DAB networks. The effect of an interference margin of 10 dB, which increases the minimum required field–strength, can be seen in *Table 4b)*.

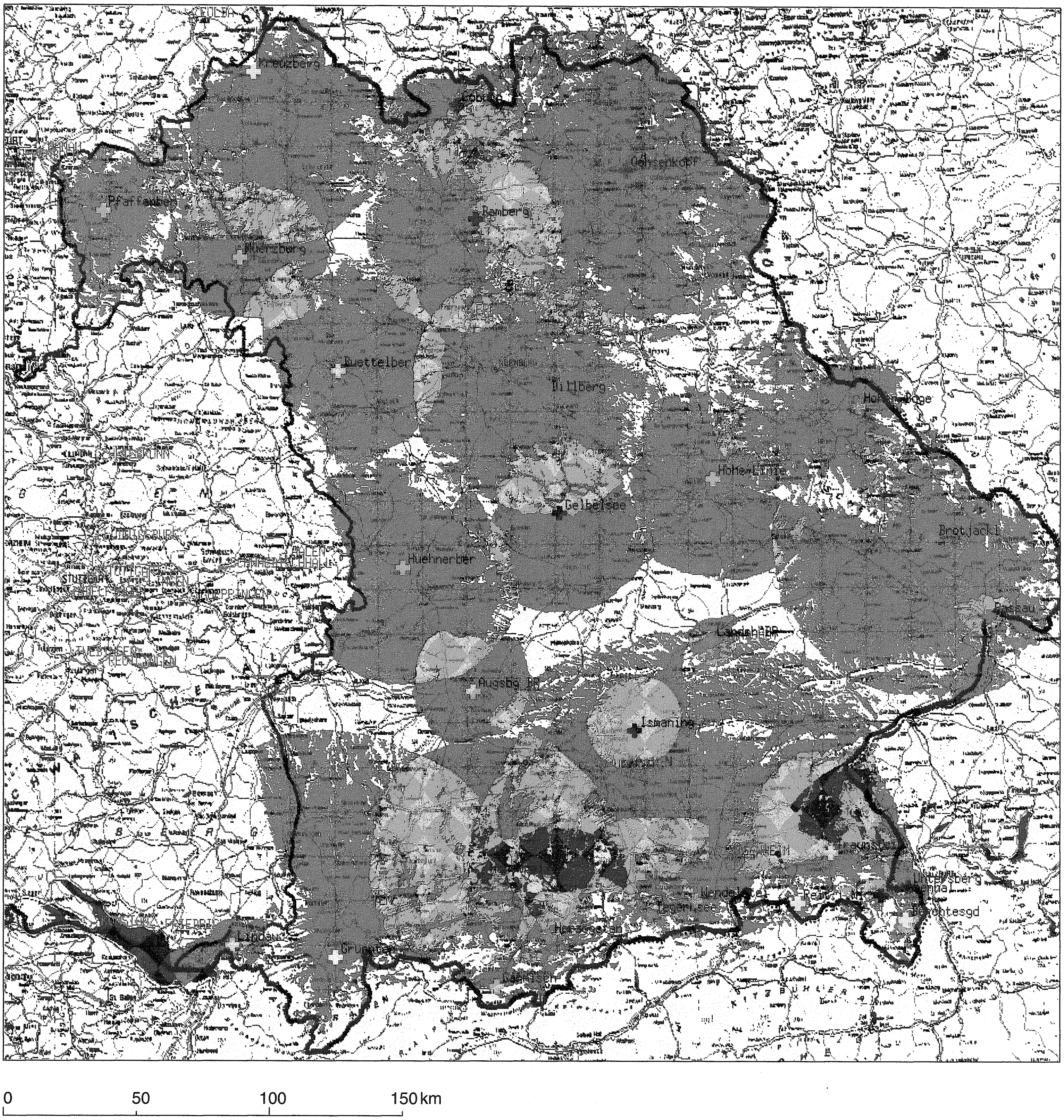


Fig. 5
DAB network using 29 VHF/FM transmitter sites of BR
Network 1

Maximum transmitter power = 1 kW

Colours indicate number of transmitters serving the pixel :
red=1, green = 2, blue = 3, yellow = 4

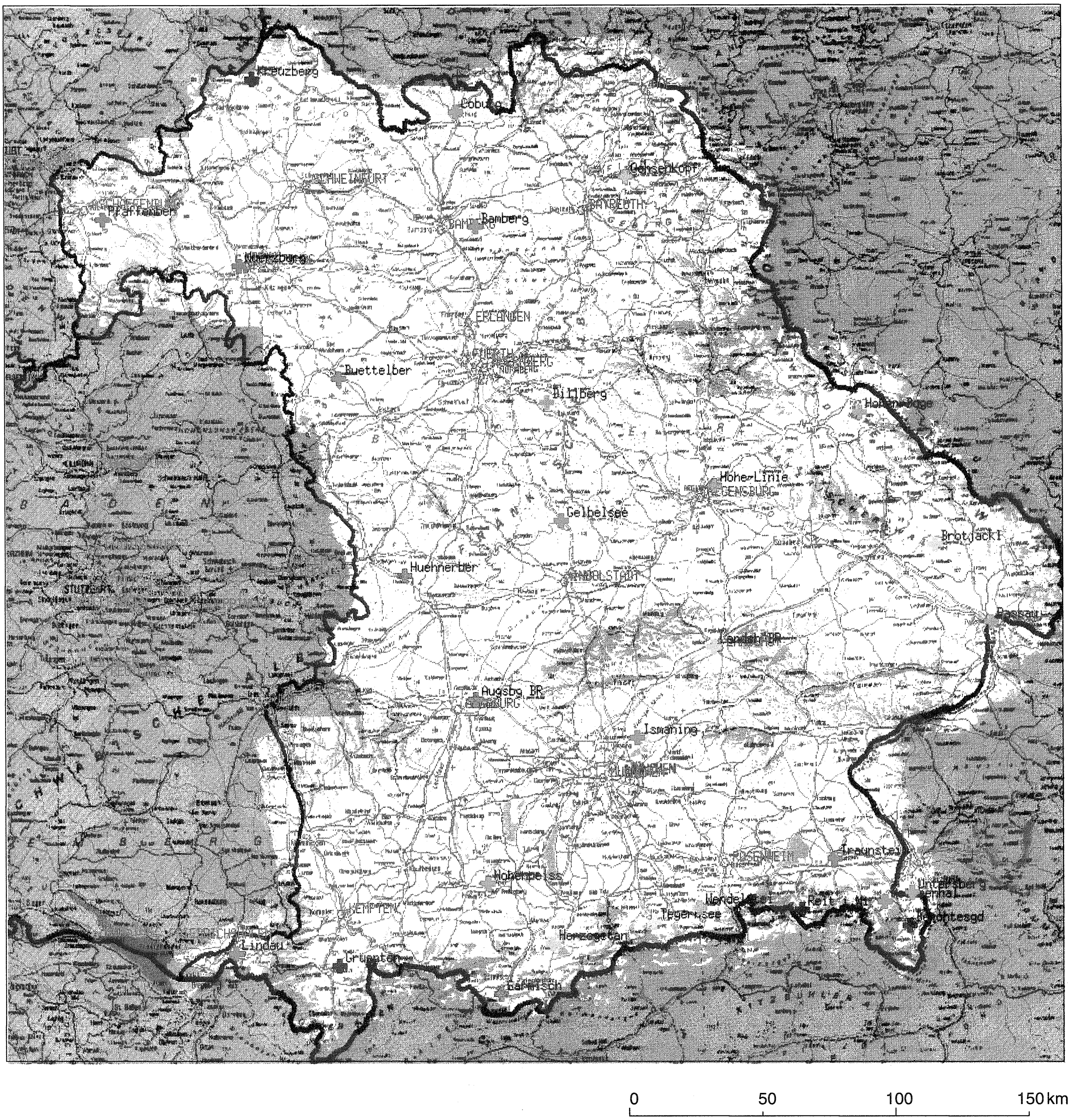


Fig. 6
DAB network using 29 VHF/FM transmitter sites of BR (as *Fig. 5*)
Network 1

Maximum transmitter power = 1 kW – Coverage taking account of power addition of the signals

Colours indicate number of transmitters serving the pixel :
red=1, green = 2, blue = 3, yellow = 4

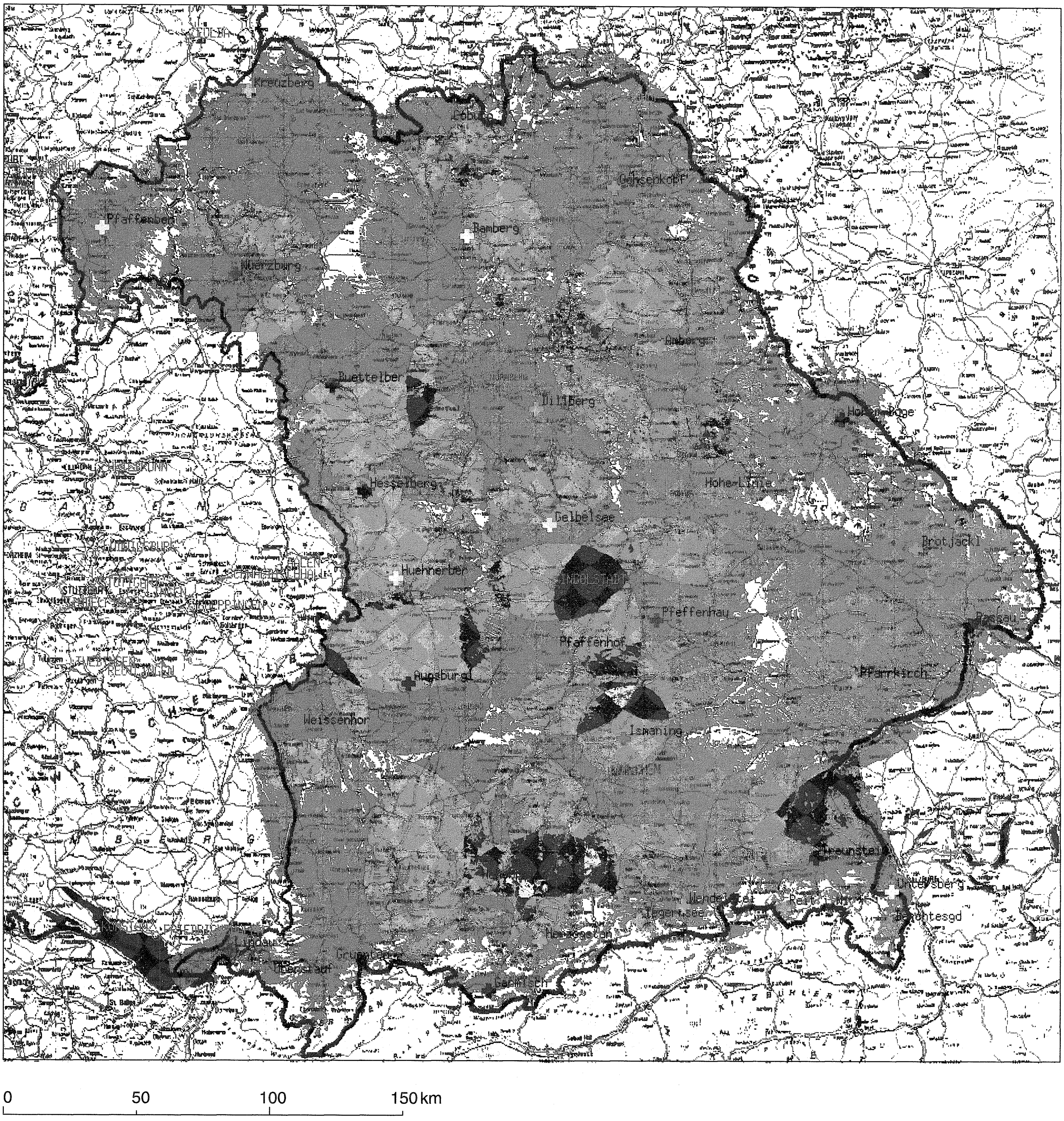


Fig. 7
DAB network using 35 VHF/FM transmitter sites of BR and DBP–T
Network 2

Maximum transmitter power = 1 kW

Colours indicate number of transmitters serving the pixel :
red=1, green = 2, blue = 3, yellow = 4

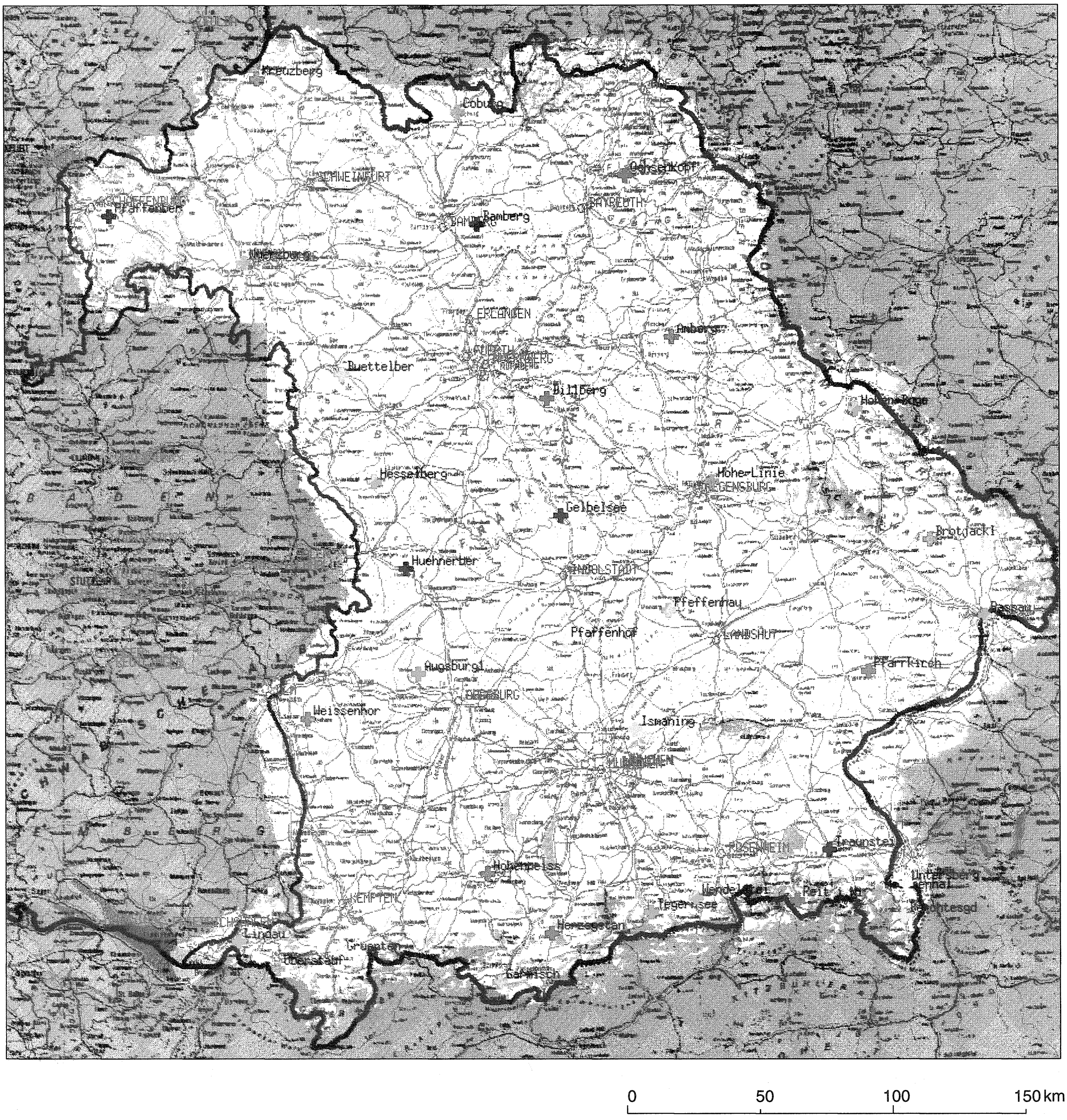


Fig. 8
DAB network using 35 VHF/FM transmitter sites of BR + DBP–T (as *Fig. 7*)
Network 2

Maximum transmitter power = 1 kW – Coverage taking account of power addition of the signals

Colours indicate number of transmitters serving the pixel :
red=1, green = 2, blue = 3, yellow = 4

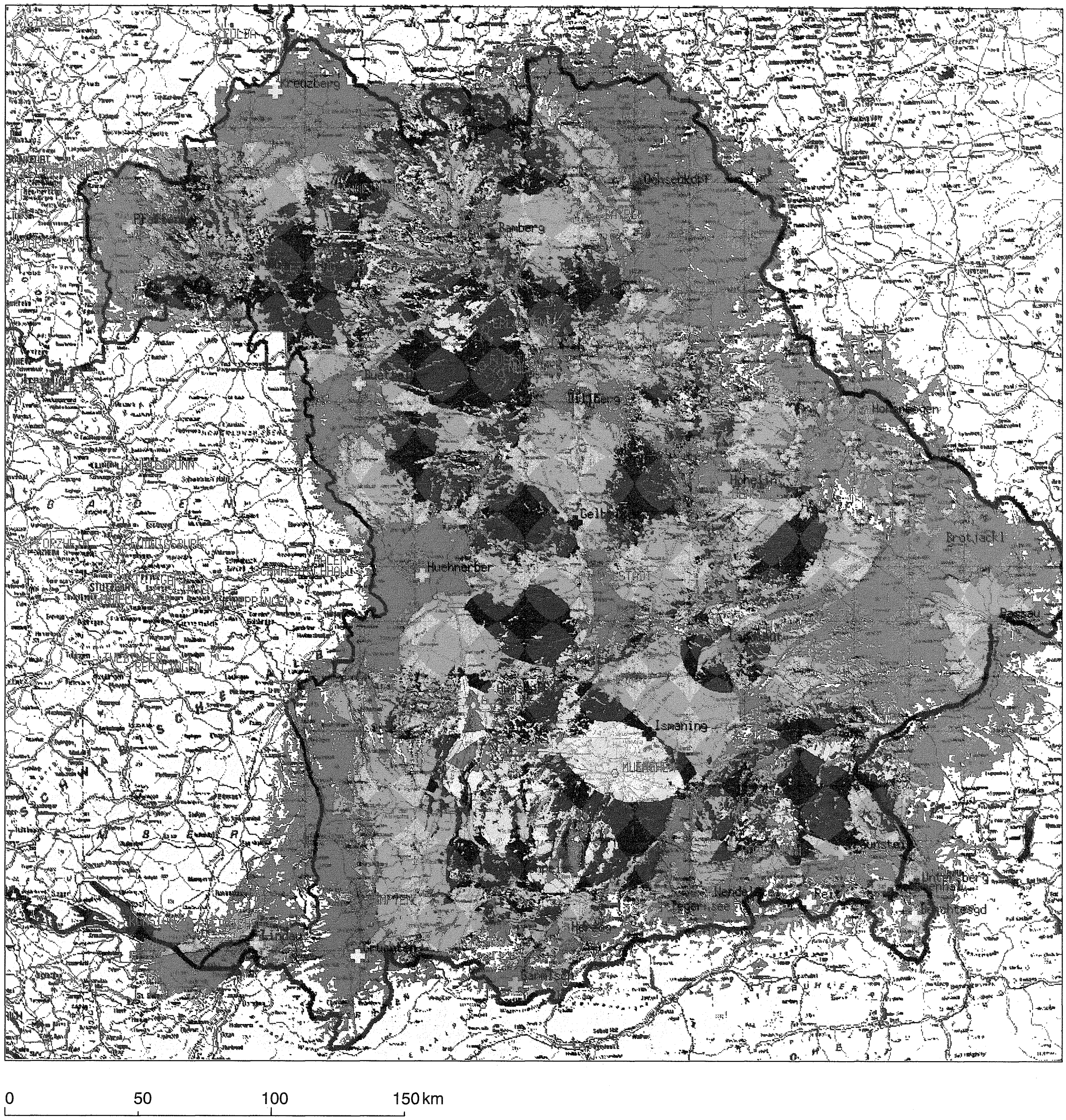
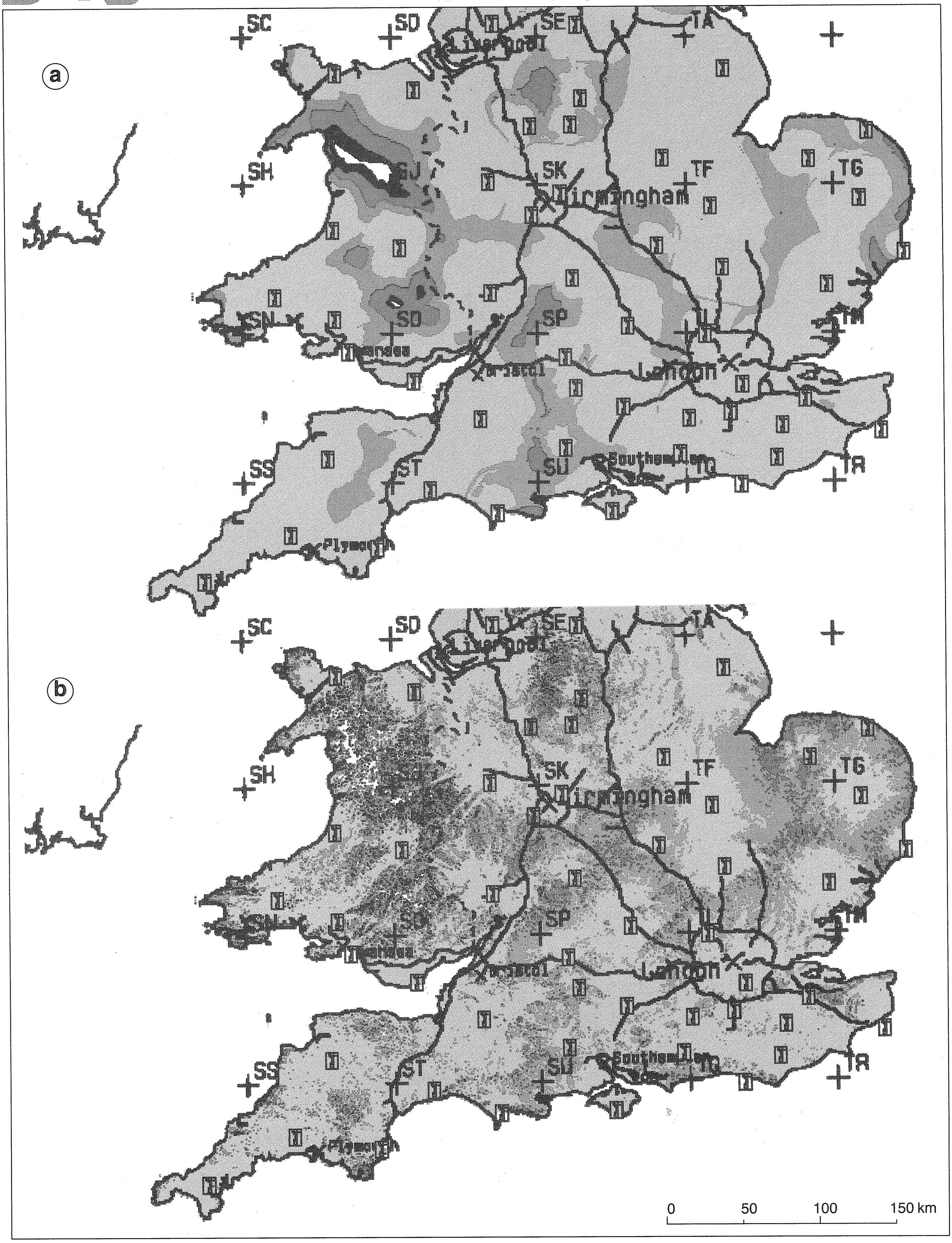


Fig. 9
DAB network using 29 VHF/FM transmitter sites of BR (as *Fig. 5*)
Network 3

Maximum transmitter power = 10 kW

Colours indicate number of transmitters serving the pixel :
red=1, green = 2, blue = 3, yellow = 4


a
b
SC
SD
SE
TA
SH
SJ
SK
TF
TG
SN
SO
SP
TM
SS
ST
SU
TQ
TR
Liverpool
Birmingham
Bristol
London
Southampton
Plymouth
0
50
100
150 km

a) without interference margin

Parameters		DAB single frequency networks		
		Network 1 29 sites e.r.p. (max.) = 1 kW	Network 2 35 sites e.r.p. (max.) = 1 kW	Network 3 29 sites e.r.p. (max.) = 10 kW
Coverage area with PSM (km²)		66900	71500	79200*
Coverage as % of Network 3		88.4	90.3	100.0
Coverage area without PSM (km²)		59600	66600	75500
Coverage as % of Network 3 with PSM		75.2	84.1	95.3
% gain attributed to PSM		10.9	6.9	4.7
% of individual pixels covered by *n* transmitters	$n = 1$	80	63	42
	$n = 2$	18	33	34
	$n \geq 3$	2	4	24

b) with interference margin of 10 dB

Parameters		DAB single frequency networks		
		Network 1 29 sites e.r.p. (max.) = 1 kW	Network 2 35 sites e.r.p. (max.) = 1 kW	Network 3 29 sites e.r.p. (max.) = 10 kW
Coverage area with PSM (km²)		36100	47300	65200
Coverage as % of reference area *		45.6	59.7	82.3
Coverage area without PSM (km²)		28900	36800	55000
Coverage as % of reference area *		36.5	46.5	69.4
% gain attributed to PSM		20.0	22.2	15.7
% of individual pixels covered by *n* transmitters	$n = 1$	97	95	78
	$n = 2$	3	5	20
	$n \geq 3$	0	0	2

Table 4
Comparison of the three SFN networks investigated by BR

PSM = power sum method
Area of Bavaria = 70553 km²
* Reference area 79200 Km²

Similar statistical calculations were performed as above and the results are given in *Table 4b*. The application of the PSM now gives an apparent gain of between 15% and 20%, whilst the coverage of Network 1 drops to 45%.

Only Network 3 has a large enough margin to give acceptable results under these worst case conditions, where a general margin for interference was introduced. In reality the coverage will lie in between the two cases compared in *Table 4*. The interference from other DAB networks depends amongst otherthings on the geographical separation of the transmitters, their e.r.p.'s and the level of the unwanted signals as well as their statistical distribution in location and time. As shown in *Fig. 4* this needs to be investigated further.

Fig. 10
DAB single frequency network for the southern United Kingdom

a)
Protection margins calculated using the prediction model of CCIR Recommendation 370

b)
Protection margins based on the BBC prediction model using a terrain data base.

Colours indicate the protection margin:
blue = <10 dB, red 10 to 15 dB
green 16 to 21 dB yellow ≥ 22dB

6.2. The United Kingdom experience

To assess applicability of the SFN technique in practical cases, predictions have also been carried out by the BBC for a network intended to provide national coverage within the United Kingdom. The method used was very similar to that described in *Section 6.1.*, except that the pixel size was 1 km². The following assumptions were made:

- Transmitters are co–sited with all main stations of the UHF television network.
- Transmitting antennas are a few metres below the UHF television antenna, or a similar dis-

tance below the lowest broadcast antenna where the site is shared by other broadcast services.

- All these stations are assumed to have radiation patterns similar to those for UHF television and a maximum e.r.p. of 1 kW per stereo programme.
- Wanted field strengths are based on 50% time conditions and interference on 1% of time.

The first assessment was carried out using the propagation model of CCIR Recommendation 370. After the coverage achieved both in terms of field–strength and protection margins had been assessed, some additional relays of 100 W e.r.p. were included and the powers of a few of the original stations which caused large overlaps were reduced to 300 W.

About 100 stations in all have been considered so far. No particular attempt was made to ensure complete coverage in the mountainous and sparsely–populated areas of Scotland (not shown) and central Wales, for which a much more–detailed study is required. The result of this analysis, using the propagation model of CCIR Recommendation 370 is indicated in *Fig. 10a)* which shows the resulting protection margin. A corresponding plot of field–strength contours, based on appropriate 6 dB banding levels, is almost identical. In other words, the coverage determined by protection margins corresponds closely to that determined by field–strength, for the power chosen. This would seem to be a desirable requisite for efficient planning.

Results of a second study using a more–detailed propagation model based on terrain information are shown in *Fig. 10b).* Here it can be seen that the protection margin distribution is different to that given in *Fig. 10a)* which was calculated using the statistical method of Recommendation 370. This is a consequence of taking account of terrain variations near the receiving location, which results in a much greater variation and a higher probability that the levels of individual signal contributions will not be inversely related to path length. (Note: in the prediction it is assumed that the reference transmitter at any location is the one which produces the highest field–strength.) The additive contribution of reflected signals, which cannot be taken into account with any certainty using current prediction methods, may reduce this local variation in margin. The effective radiated powers quoted were for mobile coverage and a single stereo programme; if the service is to be available in buildings, on portable receivers, then additional power will be required. Provisional results from measurements in London give a figure of 7 dB and this will be assumed until more reliable information becomes available. Future BBC predictions will be made using the field–strengths applicable to the total 1.5 MHz bandwidth now adopted by the Eureka 147 consortium.

An unpublished theoretical study carried out in the BBC concerning an SFN based on a lattice of equilateral triangles showed that the most efficient method of obtaining coverage is a network of closely–spaced (approximately 35 km) low–powered transmitters. This study did not, however, rule out the use of existing television station sites.

7. Future outlook

Within the United Kingdom and Bavaria, various experiments are being undertaken with a view to defining accurately the planning parameters required for an efficient digital audio broadcasting network. As shown in *Section 6* planning has started using both terrain–based and statistical methods of prediction. This work will continue and will be supplemented by additional field work.

Work has also started on low–powered Band III SFNs in both countries, in London and Munich.

These SFN evaluations are being used to test computerised data–logging measuring equipment with a view to automating field–strength and bit–error rate measurements for future use during coverage surveys. In addition, high–power tests with SFNs in Band I and channel 12 are scheduled for 1993 in Bavaria, Berlin and the Rhine valley area where transmitters will be sited in Switzerland, France and Germany. Third–generation DAB hardware with a bandwidth of 1.5 MHz will be used and the programme source will be the 20/30 GHz transponder on the Kopernicus satellite.

In the BBC, the single frequency network transmitters are being used to evaluate building losses. This data is necessary in order to specify fully the required transmitter powers so that portable receivers in buildings can be adequately served. The test transmissions are also being used to determine the effect of multiple contributions to the wanted signal level within an SFN. Further practical studies on SFNs using low–powered closely–spaced transmitters will continue. The ultimate intention of both organizations is to develop a DAB measurement technique which will enable service area coverages to be defined accurately during normal programme periods, and the existing prediction methods will be extended to enhance the accuracy achieved. As an example of this work, the clutter, i.e. buildings, trees, etc, of the city of Munich has been digitised to a resolution of 5 x 5 metres with a view to allowing the clutter effects to be incorporated into the CATS prediction program.

From the proposed experiments, and those already taking place, information related to DAB on the following topics should become available:

- The effect of obstacles (trees, buildings, etc).
- Fringe service area quality.
- Interference between DAB frequency blocks.
- Interference from DAB to other services and vice–versa.
- Polarization and frequency effects.
- Bit–error ratios in various environments and reception conditions.
- Necessary e.r.p.s for an SFN, taking into account man–made noise levels.
- Number of sites needed in a given area.
- Required percentage location coverage for mobile and portable receivers.
- Experience of coverage in all environments, particularly in large cities.
- Revised prediction models.
- Satellite distribution to single frequency networks.

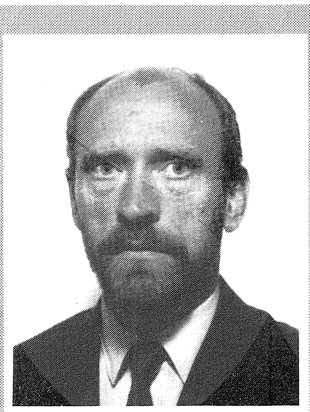
8. Conclusions

The advent of the Eureka 147 digital audio broadcasting system has realised the radio broadcasters' dream: a radio transmission system that can provide a high–quality stereophonic service to mobile, portable and fixed receivers in any environment.

A number of countries have expressed a wish to start DAB services as early as 1995 and many more will wish to start before the turn of the century. However the establishment of DAB services has to be approached by service planners in a pragmatic way, since if service coverage is lacking in any way, the take up of the system may be slow and the Eureka 147 system will not realise its full potential.

This article gives a brief introduction to DAB and its application in a single frequency network, and presents some of the studies on protection ratios that have been undertaken to date. With the adoption of the 1.5 MHz block bandwidth, further work in this field is required.

Minimum field–strengths have been established to enable preliminary coverage planning exercises to be undertaken and examples of planning exercises, using the terrestrial single frequency network concept, by the BBC in the United Kingdom and Bayerische Rundfunk in Bavaria are presented. Existing broadcast sites have been used but additional filler stations will be needed in dense urban areas to overcome building losses.



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It must be stressed that the results given here are only provisional since the development of DAB planning techniques is an on–going process. The field trials discussed will add to our knowledge and enable present planning techniques to be refined. Without adequate service planning criteria the ultimate coverage of any DAB network cannot be accurately defined.

It is hoped that the information contained in this article will encourage other organizations to perform some preliminary planning exercises and so add to our current knowledge.

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The authors would like to acknowledge the work of their many colleagues in the broadcasting organizations, the Eureka 147 project and the EBU; without their work this paper would not have been possible.

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