DAB Coverage Planning

Ofcom

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ÆGIS spectrum engineering

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1 INTRODUCTION

This report provides a review of the assumptions underpinning the planning of DAB radio services in the UK.

The derivation of the different technical parameters and assumptions used in the planning process has been critically reviewed, paying particular attention to their empirical justification.

Two sets of measurements have also been made as part of the present study; in the first a small sample of portable DAB receivers have been characterised in terms of their sensitivity and selectivity, and the results compared with relevant standards.

The second measurement campaign has examined the performance of DAB car radios in realistic conditions.

1.1 Scope

This document is concerned with the planning of broadcast DAB services in respect of RF parameters such as field strength and interference. Issues relating to frequencies other than those in Band III (174–240 MHz) have not been considered.

This document is not concerned with issues relating to audio coding, bitrates and quality, nor with multiplexing issues.

1.2 UK planning limits

DAB planning parameters are set out in the Ofcom document "*Technical Policy Guidance for DAB Multiplex Licensees*" [Ofcom, 2006].

This document notes that new DAB transmitters (i) must avoid causing interference to existing, co-channel, services (ii) should not serve 'overspill zones' beyond the licensed coverage area and (iii) should not cause interference to DAB services in the same area.

The last requirement relates to the need to avoid 'hole-punching' to existing networks due to the use of non-co-sited transmissions. Such transmissions will, inevitably, cause the necessary protection ratios to be infringed for some area around the new site. There is, therefore, a strong incentive to co-ordinate transmitter sites where possible, and this is formalised through the 'Reserved Assignment List'. This list, drawn up collaboratively by multiplex and transmission operators and Ofcom, identifies locations that are likely to be useful for DAB coverage and (i) requires use of the site to be on a non-exclusive basis and (ii) makes explicit to all operators that any other licensees in the area may be expected to use the site at any time.

The technical planning standards are set out in Section 5 of the Ofcom document, and are specified in terms of the median field strength at 10 m above ground, with predictions made to the centroids of 100 m x 100 m squares. Two thresholds are used:

- **58 dB(μV/m)** [a mobile listening environment, and above a first floor level indoors, on typical portable receivers]
- **65 dB(μV/m)** [indoor reception, in the majority of domestic buildings].

Within the licensed area, a protection ratio of 25 dB is to be ensured for 99% of time. The document notes that "*… this is based on calculation, supported by field trial data gathered in 1997 by Ofcom's predecessor, The Radio Authority*).

Revised planning criteria are currently being developed. These leave unchanged the 58 dBμV/m figure for mobile coverage, but give four criteria for indoor coverage. In dense urban areas 'useful' coverage is defined to be provided for a 10 m field strength of 71 dBμV/m and 'robust' coverage at 77 dBμV/m. In other areas, the corresponding limits are 64 dBμV/m and 70 dBμV/m.

1.3 Evolution of planning limits

An early attempt to define planning limits for DAB services is given in [Bell, 1993], in which a required C/N of 10 dB was assumed[1]. Further assuming a receiver noise figure of 8 dB an aerial gain of −2 dBd and a height gain of 12 dB, a minimum field strength at 10 m of 41 dBμV/m is derived. Further allowances were made for man-made noise (a 4 dB uplift) and for location variability (a median to 99% uplift of 12 dB[2]) to give a planning value of median field strength of **57 dBμV/m** at 10 m.

BBC field trials carried out in 1994 using a pre-operational network of four medium-power sites in London and third-generation test receiver are reported in [Maddocks, 1995]. Measurements made to determine service limits "*… showed a wide variation in field strength with a mean failure field strength of around* 41 dBμV/m" (at 1.5 m), although it was noted that the test receiver itself was a significant source of man-made noise.

In 1995, the roll-out of the operational BBC DAB network commenced, and in July of that year the first CEPT planning meeting for T-DAB was held at Wiesbaden. At this meeting, a minimum median DAB field strength at 10 m of **58 dBμV/m** was assumed (based on a minimum FS at the 1.5 m high aerial of 35 dBμV/m, in turn assuming a required C/N of 15 dB). This value was derived at a frequency of 230 MHz, and applied across the band. *Protection against co-channel DAB transmissions assumed a required 10 dB C/I margin, and that wanted and interfering signals had a location variability of 5.5 dB. These assumptions led to a maximum interfering field strength of 30 dBμV/m (median, 10 m).*

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[1] But with a note that "*recent studies indicate that a higher value may be required*".

[2] This value implies a location variability of 5.2 dB. The currently agreed value of 5.5 dB was adopted shortly after this paper.

The Radio Authority considered [Thomas, 2002] the DAB service limit to be **47 dBµV/m at 1.5 m agl**. This was based on a 37 dBµV/m minimum FS, with a 99% location correction factor of 10 dB based on σ=4.3 dB. This limit would correspond to the 58 dBµV/m limit if a height gain of 11 dB is assumed.

At the GE-6 planning meeting a slightly different limit of **60 dBµV/m** was adopted for mobile DAB reception, the difference being due to the larger corrections assumed for height gain and for man-made noise. This limit is derived at the ‘reference frequency’ of 200 MHz, and for 224 MHz (roughly the centre of the present UK DAB band) should be corrected to 61.5 dBµV/m. The RRC also adopted a planning limit for indoor reception of **66 dBµV/m**.

2 REVIEW OF PLANNING PARAMETERS

2.1 Introduction

The following section give a brief review of the assumptions made regarding the different parameters required for DAB service planning. In most cases, a summary is given of the parameter values quoted in different documents over the years, and the evolution and empirical basis of adopted values is traced. The empirical evidence is reviewed, and any concerns or issues highlighted.

2.2 Receiver sensitivity (C/N requirement)

2.2.1 Required BER at MPEG decoder input

The DAB system uses MPEG-1, Layer II audio coding, and subjective tests [Gilchrist, 94], [Gilchrist, 1996] have shown that this CODEC will produce audible errors (Onset of interference, or 'OoI') for a BER of around 5×10^{-5} with complete failure at a BER around 10^{-2}. A value of 10^{-4} is suggested as an appropriate target service limit.

An ITU-R Recommendation[3] of 1994 [BS.774-1] stated that "p*rovisional assessments of sound quality indicate that it is not perceptibly impaired if the BER is less than* 10^{-4}".

2.2.2 Required C/N at demodulator input

The OFDM modulation scheme used in the Eureka 147 DAB system uses QPSK modulation, differentially decoded. D-QPSK in isolation gives a low theoretical C/N requirement of around 12 dB in a Gaussian channel for a BER of 10^{-4}.

In practice, most systems will use additional forward error correction (FEC) to add redundancy, and hence, robustness, to the transmitted signal, and this will change the effective failure point of the system, as will the nature of the transmission channel (Gaussian, Ricean, Rayleigh) and the details of the receiver implementation.

2.2.3 Coding in the DAB system

In the DAB system, FEC is added through the use of a convolutional code, generally decoded using a soft-decision Viterbi decoder. The coding is applied at different rates to different parts of the transmitted signal, so that some parts (e.g. audio scale factors) are more heavily protected than others (sub-band audio samples). This 'Unequal Error Protection' (UEP) scheme ensures that the FEC overhead is apportioned in the most effective way in terms of subjective perception of degradation. The DAB system specifies five protection levels (PL-1 being the most robust, PL-5 the least), which can be applied independently to different components of the multiplex. As different redundancy is applied to different components, these

[3] The precursor of BS.1114.

are often characterised by the *average* code rate, and this will vary slightly with source bitrate, as shown in Table 2.1.

Table 2.1: DAB code rates and UEP protection levels [ETS 300 401]

Audio rate	Protection level				
	1	2	3	4	5
96	0.35	0.43	0.51	0.62	0.75
128	0.34	0.41	0.50	0.57	0.75
192	0.35	0.43	0.51	0.62	0.75

Laboratory testing [Gilchrist 1994], found that moving from PL-4 to PL-3 (from ~0.6 to ~0.5 code rate) gave an improvement of around 1.5 dB in the system robustness[4]. In the UK, protection level 3 is most generally applied.

2.2.4 C/N in the Gaussian channel

The simplest C/N requirement to define is that necessary when both the carrier and noise power densities are constant in frequency and time domains, i.e. in a Gaussian channel. A full description of the different measurements and recommendations regarding the Gaussian C/N requirement is given in Annex B.

Measurements quoted in an early ITU-R Recommendation [BS.774-1] suggested a 7.1 dB C/N value for Mode 1, PR 3. This was simplified to ‘7 dB’ for the WI-95 planning process.

A revision of the recommendation (1995) gave a value of 7.6 dB (Mode I) and 7.4 dB (Modes II and III). The latter value appears to have been adopted for all modes in the relevant EBU technical note [BPN-003].

Measurements made in 1994 and 1996 suggest a value of around 6.8 dB for the ‘onset of interference’ in Mode 1, PR3. There is a variability in subjective assessment of failure of around 1 dB depending on source material.

The difference between the onset of impairment and complete failure is around 2–3 dB.

The value of 7.4 dB given in BPN-003, although strictly determined from measurements made in Mode II, seems perfectly realistic. The Gaussian C/N is, however, never used in practical planning.

2.2.5 C/N in the Rayleigh channel

In any practical scenario, a DAB receiver will not experience a Gaussian channel. The wanted signal will be varying in amplitude, will exhibit a temporal delay spread and will probably be subject to some Doppler fading due either to its own motion or that of surrounding objects.

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[4] All values quoted relate to Mode 1 operation in Band III.

Although COFDM is a robust modulation scheme, these channel imperfections will imply that a higher C/N will be required at the input to the demodulator to deliver a given bit error rate at the output.

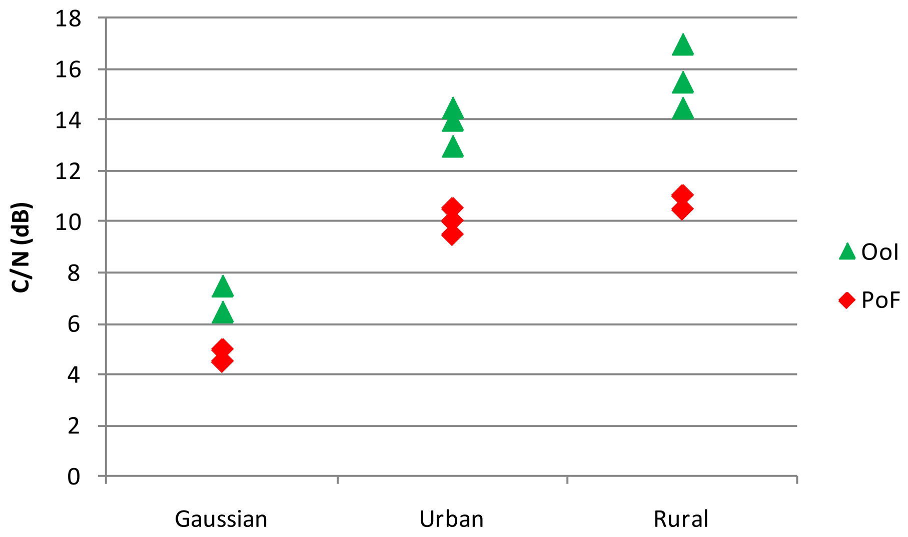

Figure 2.1: Measured C/N thresholds (Mode I, Code rate 0.5)

A survey of the assumptions and measurements made regarding C/N requirements in the fading channel can be found in Annex B. Of particular note is the apparent paucity of evidence for the use of the COST 207 channel models for Band III DAB.

Summary: For fast-fading rural or urban channels as modelled by the COST 207 profiles, a C/N of around 15 dB or 12 dB is required. How accurate the COST 207 models are when applied to DAB networks at 200 MHz (using SFNs) is not clear, and neither is the correspondence with UK area or population coverage.

Planning values for C/N in a Rayleigh channel of 13 dB, 14 dB and 15 dB are given in BPN-003, TR 101 758 and the Wiesbaden 95 plan respectively.

2.3 Noise

2.3.1 Receiver system thermal noise

Having determined the necessary C/N value, it remains to quantify the noise to be expected, referred to the receiver input. This noise will include the thermal and other noise generated by the receiver circuits and aerial feeder, atmospheric and galactic noise, and man-made environmental noise.

While much of this noise can be assumed to be Gaussian, and thus additive in power, some of the most significant degradation to DAB performance may be due to impulsive, man-made noise for which a much more complex treatment is (formally) required.

It is a simple matter with the active devices currently available to engineer receivers with a noise figure well below 1 dB at 200 MHz. For broadcast reception, however, it is necessary to accommodate a very wide dynamic range (typically 80 dB) of signals at the input, while avoiding intermodulation and other non-linear effects. This implies a necessary reduction in the noise figure that can be attained.

Commercial Radio Australia (CRA) have tested [Dickson, 2008] a number of DAB receivers, and found the noise figures to range from 4.1 to 9.0 dB.

In [TR 101 758] a value of 6.0 dB is suggested as a target value for receiver design, though no detailed justification is provided for this figure beyond references to 'typical examples'. Nonetheless, the value seems entirely reasonable based on the experience of the present author.

No value for noise figure is given in [BS.1660-3] for DAB systems[5], but the planning for RRC-06 assumed a figure of 7 dB (stated in [ITU, 2006] with no justification). The same 7 dB figure is assumed for UK planning.

[EN 50248] quotes '<3 dB' as the typical noise figure for an active antenna.

2.3.2 Man-made noise

In most derivations of minimum signal strength, though not in [TR 101 758], an explicit allowance is included in the link budget for man-made noise. In most cases this is assumed to be 1 dB, e.g. [ITU, 2006], [BPN-003]. Measurements made by the BBC [CEPT, 1994] report measurements of ambient noise, which, at Band III, was found to be significantly lower than the thermal noise of a typical receiver.

In [Pullen, 2004] it is noted that levels of environmental noise are some 10 dB greater at Band II (~100 MHz) than at Band III, and the impact of coverage is discussed. In the field trials discussed in the document, however, much of the increased noise at Band II is attributed to that radiated from the amplifiers of a nearby high-power FM radio station.

No explicit allowance is made for man-made noise in UK planning, and the allowance for 'self induced EMI' is set to 0 dB.

2.4 Sensitivity

Given a knowledge of the necessary C/N for a particular channel, and the thermal noise in the receiver system, the 'receiver sensitivity' can be specified in terms of power (generally given in dBm) at the receiver input port.

This figure is relevant, and directly measurable, in the case of receivers with an external aerial connection (generally only Hi Fi tuners and car radios).

2.5 Selectivity

[EN 50248] requires that receivers have a −30 dB protection ratio for DAB signals in the adjacent channel, and −40 dB for an FM signal at ≥5 MHz from the DAB centre frequency.

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[5] Although ISDB receivers operating at 200 MHz are assumed to have a 5 dB noise figure in this Recommendation.

In 2002, it was stated [Thomas, 2002] that *"most receivers seem to perform at −35 to −40 dB*" in respect of adjacent channel protection ratio.

The measurements reported in [Schiphorst, 2008] suggested that the selectivity of most receivers is asymmetrical, with a poorer rejection of the upper adjacent channel. Of 15 receivers tested, some 25% failed to meet the EN 50248 requirement in this respect. Furthermore, 75% of the sample required a protection ratio of more than −40 dB in the upper second-adjacent channel.

2.6 Antennas

2.6.1 Assumed values

Most of the original DAB coverage criteria were derived for car reception. In [Bell, 1993] a gain of −2 dBd was assumed for a car aerial system, and the Wiesbaden planning meeting assumed isotropic gain (i.e. −2.2 dBd), as does the EBU planning note [BPN-003].

The RRC-06 planning conference [ITU, 2006] referred to [BT.1368-6] in specifying a −2 dBd antenna gain for portable reception. The Recommendation notes that "*A spread in antenna gain has been measured for different types of antenna*" and that the −2 dB figure is *"typical*".

For the mobile case, RRC-06 also assumed −2 dBd, but the Recommendation gives a value of −5 dBd, noting that "*The practical standard antenna for vehicle reception is l/4 monopole, which uses the metallic roof as a ground plane. The antenna gain for conventional incident wave angles depends on the position of the antenna on the roof. For passive antenna systems [−5 dBd] can be expected".* This value is assumed in UK planning.

UK DAB planning is understood to assume an antenna gain of −10.2 dBd for portable receivers, the value being based on measurements made by the BBC using a G-TEM cell[6].

2.6.2 Measured values

For early trials of the DAB system, the BBC used a Renault 'Espace'. A separate ground plane of 1.5 x 1.2 m was installed above the fibreglass roof of the vehicle. This accommodated ¼λ whips for 211 MHz and 531 MHz. As measurements were made at both frequencies, the radiation patterns were measured [Maddocks, 1993] with both whips in place. The results for Band III are shown below.

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[6] A ***G****igahertz* - ***T****ransverse* ***E****lectro-****M****agnetic cell* is a chamber used to generate know field strengths.

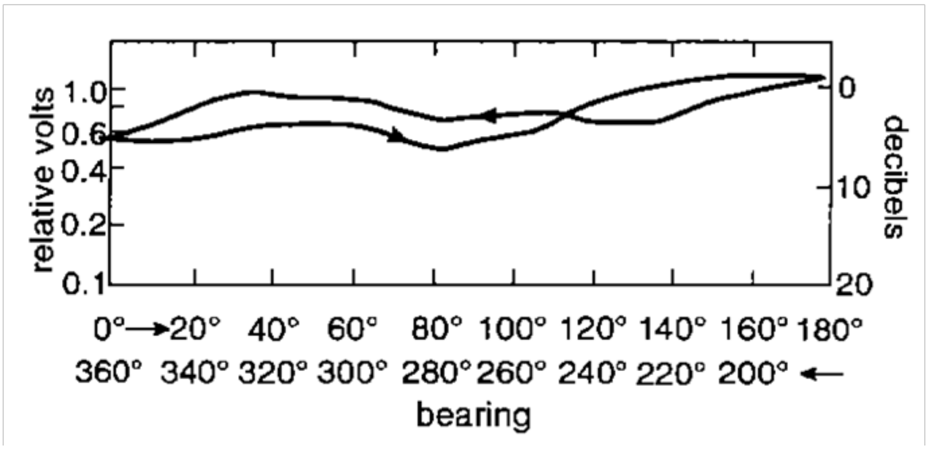

Figure 2.2: Measured azimuth pattern of ¼λ whip on rooftop ground-plane (BBC)

The measured pattern shows a variation in gain of around 8 dB with azimuth. Unfortunately, no figure is given for the absolute gain of the antenna.

In [Schiphorst, 2008] measurements made in an anechoic chamber, of three portable receiver aerial whips, are reported. These measurements suggested "*a typical antenna factor of 25 dB*". At 222 MHz, this corresponds to a gain of −10 dBd.

2.6.3 Modelled values

The 'method of moments' algorithm implemented in the NEC-2 software package was used to model the case of a quarter-wave whip mounted near the front of a saloon car roof.

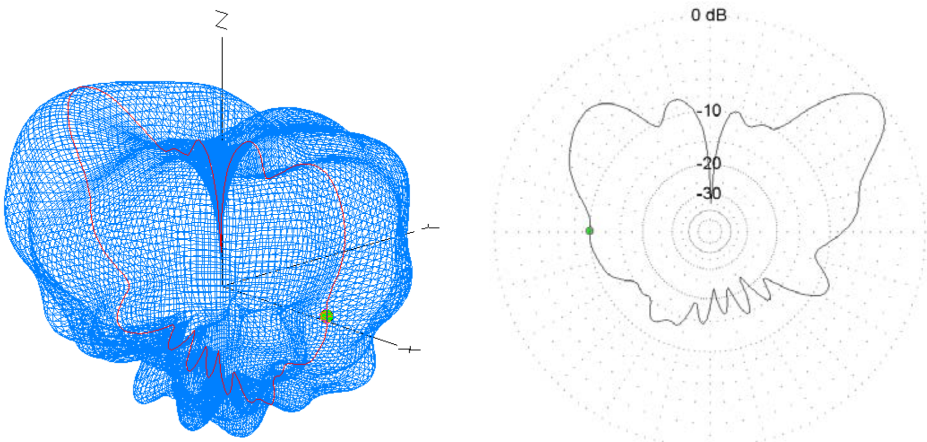

Figure 2.3: Predicted performance of quarter-wave whip on car roof

It can be seen that the pattern is distinctly asymmetric, with a maximum response (3.5 dBd) at an elevation angle of some 40°. Towards the horizon, the gain of the antenna is between −4.5 dBd and −6.4 dBd. This compares well with the −5 dBd assumption used in UK planning.

Summary: The UK-assumed values of −5 dBd and −10.2 dBd gain for car and portable antennas respectively seem realistic, although the car figure seems to be based on little, if any, measured data.

2.7 Propagation issues

2.7.1 Location variability

2.7.1.1 Assumed values

From an early stage [EBU, 1994], a value of 5.5 dB has been assumed for the location variability of DAB signals in Band III. This implies that the median field strength should be 12.8 dB above the minimum requirement to ensure coverage to 99% of locations. This 12.8 dB is often rounded to 13 dB.

The 5.5 dB figure appears to be based on measurements made in 500 m x 500 m squares using the initial BBC low-power DAB network [Maddocks, 1993]. Later, more extensive, measurements made using the high-power network gave a figure of 4.1 dB (also measured in 500 m x 500 m squares, but with a large sample of 2217 areas).

A smaller exercise using a temporary transmitter in Birmingham gave a figure of 6.9 dB, but this was measured in a rather small number (16) of squares that were much larger (1 km x 1 km).

In 2002, the RAu were apparently assuming a value of 4.3 dB in their planning, but it is noted in [Thomas, 2002] that measurements in the Chelmsford area suggested a lower value (measured in 250 m squares).

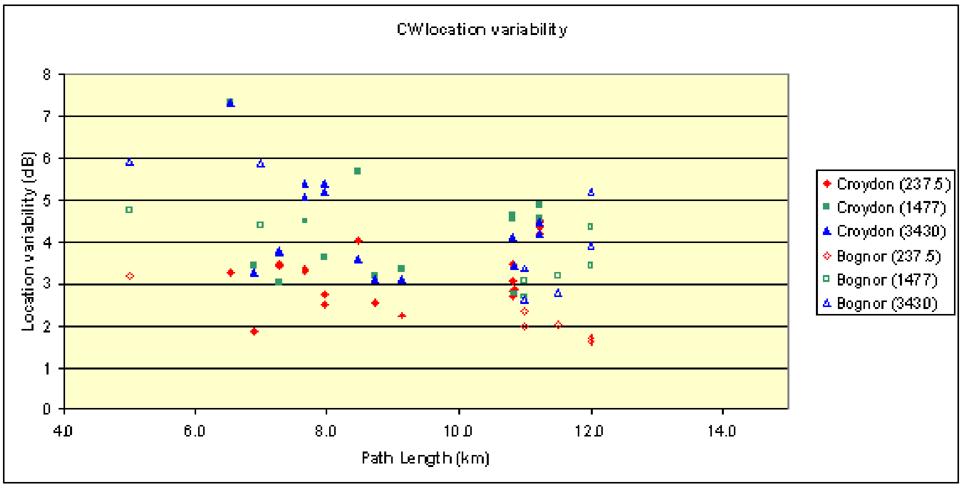

Figure 2.4: Measurements of location variability (Aegis)

During the development of ITU-R Recommendation P.1546, Aegis Systems carried out, on behalf of Ofcom, an extensive set of measurements of location variability (at 237 MHz, 1.5 GHz and 3.4 GHz) using narrowband and wideband methods in parallel. These suggested that the location variability at VHF (in areas 500 m x 500 m) is of the order of 3 dB ± 1 dB. The measurements form the basis for the current location variability model in P.1546 and P.1812, although, in both cases, the 5.5 dB value is retained in parallel in response to requests from broadcasters[7].

2.7.2 Height gain

In general, it will be found that a lower field strength is received at 1.5 m height above ground than at 10 m. This is due partly to the additional diffraction losses on the path to the lower antenna in built-up areas, and partly due to the impact of interference between direct and reflected paths in more open areas. The difference between the two is generally referred to as height *gain*, although, in DAB planning, we are more concerned with the height *loss* between predictions made to 10 m and the actual field strength at car roof height.

In a preparatory document for the Wiesbaden planning meeting [EBU, 94], a figure of **10 dB** for the height gain from 1.5 m to 10 m is given. This is said to be based on "*measurements made in Germany on vertically-polarised Band III signals*". The same value was used at the planning meeting [CEPT, 1995].

The value assumed for the planning in the RRC-06 [ITU, 2006] was somewhat higher, at **12 dB** (associated with a frequency of 200 MHz, and with interpolation to be used to derive values at other frequencies (as the next frequency is 500 MHz, with an assumed height gain of 16 dB, the 12 dB figure can be assumed to apply throughout Band III).

The propagation model used in RRC-06 was based on ITU-R P.1546-2. This Recommendation incorporates a number of expressions (given in Annex 2, Section 9) for receiver height gain. Using the 'urban environment' expression of Eq.28a gives a value of **12.8 dB** for the 1.5 m to 10 m height gain if the 'representative clutter height' is 10 m, falling to 4.8 dB for a representative height of 20 m. Using the 'Rural' expression (Eq.28b) gives a rather larger figure of **15 dB**. It should be borne in mind that this is intended to be a very general model, does not take account of polarisation and is not based on any substantial set of data from Band III measurements at the heights concerned.

[7] Largely to reflect the fact that this value had been used in planning conferences, rather than on any empirical basis

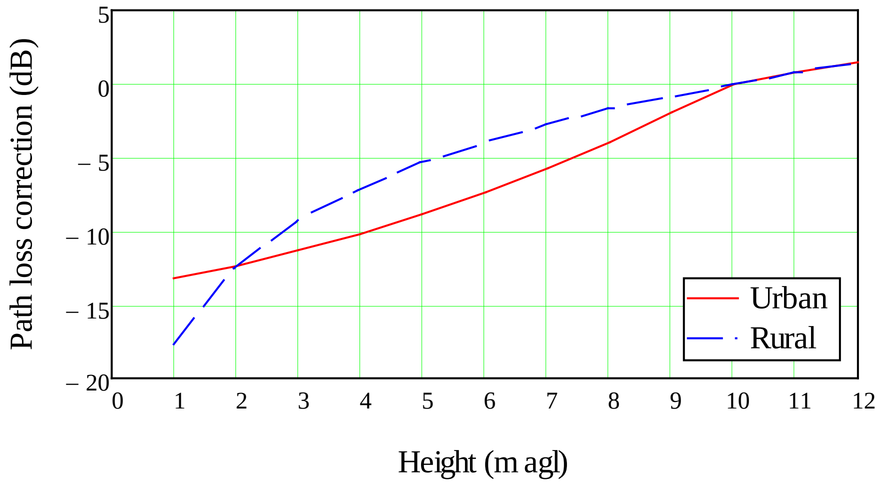

Figure 2.5: Height gain expressions in P.1546-2

In BPN-003, the height gain figure is given as **13 dB**. The next says only that this value "… *is assumed to represent realistic situations*".

2.7.3 Building entry loss

An important class of DAB reception is the use of portable receivers in the home. While FM services provide only a limited indoor coverage, this is disguised to some extent by the typically small loudspeakers available in the receivers and noisy listening environments, both of which tend to obscure analogue degradations. In the DAB case, rather than experiencing poor signal-to-noise performance, fading or multipath distortion, the user may be presented with silence. Particularly problematic is that no simple cue is available to allow the re-positioning of the receiver for best reception, if a given multiplex is not found on the initial scan.

An accurate understanding of the statistics of building penetration loss is therefore of great importance in DAB service planning. To assemble such data, unfortunately, requires a large number of time consuming measurements.

2.7.3.1 Assumed values

The WI-95 planning meeting was, formally, only concerned with planning on the basis of providing a service to vehicles. The EBU preparatory document, however, noted the requirement for in-building coverage, and referred to "*recent measurements within the UK in the VHF bands [that] indicate that the median value of building penetration loss appears to be about 8 dB with a standard deviation of approximately 4 dB*".

The Final Acts of GE-06 give the mean[8] building entry loss in Band III as 9 dB, with a standard deviation of 3 dB.

[8] Note that this figure is given as a mean rather than median value referred to in the EBU document. Is the distinction intended?

BPN-003 notes that "*A limited number of studies have been carried out to quantify domestic building penetration loss. For VHF, the values ranged from 7 dB to 8 dB"* The document adopts the 8 dB value.

It is understood that UK DAB planning assumes that a building loss of 8 dB (with 4.4 dB standard deviation) is to be assumed in rural and suburban areas, while 15 dB (with 5 dB standard deviation) should be assumed in dense urban areas. These figures are based on BBC and Arqiva measurements detailed below.

2.7.3.2 Definition

The ITU-R, rather surprisingly, provides very limited guidance on building loss, with the only relevant information being given in Recommendation P.1812 "A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands". This defines building loss as "*the difference (dB) between the mean field strength (with respect to locations) outside a building at a given height above ground level and the mean field strength inside the same building (with respect to locations) at the same height above ground level".* The same definition is given in P.1411. Values of 9 dB and 3 dB for the median loss and SD respectively are quoted for 200 MHz. The Recommendation also proposes that, as the outdoor variability of signals and the variability due to building attenuation are '*likely to be uncorrelated*', the overall indoor SD can be calculated by taking the square root of the sum of the squares of the individual SDs. The values given for 200 MHz are the same as those used in RRC-06.

In BPN-003, building penetration loss (BPL) is defined as "*The mean building penetration loss is the difference in dB between the mean field strength inside a building at a given height above ground level and the mean field strength outside the same building*".

This definition is not reflected in the measurement methods of the empirical studies summarised below, where the outside field strength is measured at ground level.

2.7.3.3 BBC Measurements

The BBC undertook a survey of building loss in 26 domestic buildings in 1992, using an initial, experimental low-power DAB network, operating with a 1.75 MHz system bandwidth. In these measurements, the field strength at 2 m outside the building, on the side facing the dominant transmitter, was taken as the reference.

The results, given in [Green, 1992] showed an average building loss to the ground floor of **7.9 dB**, with a standard deviation of 3.7 dB within a room, or **5 dB** across all ground floor rooms.

These results were supplemented [Maddocks, 1994] by measurements made in a further 13 houses, using the pre-operational high-power DAB network. Although made in more urban areas, these measurements gave very similar results, with an average loss of 8.3 dB.

2.7.3.4 Arqiva Measurements

A set of measurements were made in five commercial buildings in central London, and reported on in 2004 [Mason, 2004].In the measurements the aggregate power from an existing SFN was sampled continuously as a trolley-mounted receiver was moved around each floor of the target building. Reference measurements were also made outside the building at ground level.

The overall penetration loss values given for each building[9] appear to be the median (or average) values for all data across the floors of interest, rather than the mean of the values for each floor. It is not simple to compare the values across buildings, as some relate to all seven floors of an office block, others only to the first two floors. The study concluded that an 'average' building penetration loss of **15 dB** was an appropriate assumption for the planning of indoor services, coupled with a standard deviation within the building of **5.0 dB**.

2.7.3.5 Commercial Radio Australia

A substantial survey of building loss at Band III and L-band was carried out in Sydney in 2005. Measurements were made in 35 buildings, covering domestic, retail and commercial properties.

The reference for the measurements was established by recording external field strength at ground level on all four sides of the building, from balconies on each measurement floor and on the roof. Details of the data reduction are not made explicit in the report, but it appears that the reference used to define building loss was the largest of the four mean[10] field strengths measured at ground level outside the building. This is, therefore, comparable with the BBC and Arqiva methods.

The mean loss[11] value, for ground and first floors combined in all buildings surveyed, is **11.1 dB**. The value for domestic buildings is much lower at 4.9 dB, while commercial buildings have 'ground and first-floor' losses between 13 dB and 17 dB.

The standard deviation of the signals measured inside and outside the building was found to be almost identical, at **4.4 dB** and 4.3 dB respectively. The report does not describe the derivation of these standard deviations, however, so it is unclear whether they are average figures for room SD, average figures for building SD or simply the standard deviation of all measurements made in all buildings.

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[9] The summary table on the last page seems to give an incorrect value for the loss in 'Classic FM house' —from an earlier table this should be 14.81 rather than 15.25 dB.

[10] One might have expected the median value to be used as the reference, but the results tables suggest otherwise.

[11] 'Loss' values are generally given as negative figures, presumably an editorial error.

2.7.3.6 Discussion

The measurements made are broadly comparable, as all are referenced to the outdoor field strength at ground level. In the BBC and CRA results, the measurements made on the 'best-illuminated' side of the building were used; the Arqiva results only record that the "… *measurements were repeated outside the building at ground level to give a mean field strength for outside*". For the measurements made other than on the ground floor it may be noted that this method is at variance with the definitions given by the ITU and EBU.

The Australian data suggests that domestic buildings have a building loss some 3 dB lower than in the UK (BBC measurements). It had been expected that this might be due to lighter construction (e.g. timber) materials in Sydney compared with Surrey, but this is not obviously the case when the site photographs are examined.

There is a good correspondence between the measurements made in commercial buildings, with values of 9–15 dB recorded in London and 13-17 dB in Sydney. The buildings in Sydney are in a significantly less-dense environment, but as the reference for both sets of measurements was the field strength recorded at street level immediately outside the building this may not be relevant except for upper floors. Values used in planning, and those measured, are summarised in Table 2.2, below.

Table 2.2: Summary of building loss data & assumptions

	BPL	**SD**
Wi-95	~ 8 dB	~ 4 dB
GE-06	9 dB	3 dB
P.1812-2	9 dB	3 dB
BPN-003	8 dB	3 dB
BBC (domestic)[12]	8 dB	4 dB
Arqiva (commercial)	15 dB	5 dB
CRA (commercial)	13–17 dB	4.3 dB
CRA (domestic)	4.9 dB	4.3 dB

The treatment of standard deviation gives some cause for concern. The BBC report does explicitly give SD values for 'worst room', 'best room' and 'whole floor', although the fact that the latter have the lowest values seems counterintuitive. This may be due to the SD values being values averaged across all houses measured, rather than SD values for the entire, normalised, dataset. It is not clear how the SD values given in the other reports are derived.

[12] Summary value from [Maddocks, 1995].

It is interesting to note that the BBC and CRA studies record that the SD measured outside and inside are very similar. It is not clear to the author that there is necessarily any statistical justification for the combination of 'outdoor' and 'indoor' variabilities as is suggested in, e.g. BPN-003 or the Arqiva paper.

For domestic reception, it appears that a figure of around 8 dB may give a reliable estimate of median building penetration loss. This value is, however, based on only a small sample of homes for which structural and location data is not given in [Green, 1992] or [Maddocks, 1994]. If some homes in dense urban areas have entry losses more typical of commercial buildings, or if basement rooms are to be covered, it seems that an assumed median building loss of some 15 dB would be more appropriate, and this is the approach now adopted in UK planning.

2.8 Summary & conclusions

The parameters associated with DAB service planning are, in most cases, quoted with slightly different values in different documents. In most cases, these different values adopted simply reflect statistical uncertainty (for example, in the characterisation of height gain, or the required C/N in different Rayleigh channels).

Certain issues do, however, stand out as perhaps demanding further study.

The characterisation of receive aerial gain does not appear to have received the attention that might have been expected. In most planning documents, a 2 dBi figure is given, which would imply a sensitivity in excess of that actually measured (see Section 3).

In determining the required values of C/N in fading channels, the channel profiles from COST 207 have been widely applied. No explicit comparison appears to have been made between the characteristics of these profiles, and the channel statistics actually seen by a DAB receiver in typical environments.

3 PERCENTAGE TIME AVAILABILITY TARGETS

Most terrestrial radio systems are potentially vulnerable to short-term interference from distant transmitters, occurring when normally high path losses are significantly reduced due to ducting, or related phenomena, in the troposphere.

The UK DAB networks are planned on the basis that they shall be free of such interference for 99% of the time [Ofcom, 2006]. The co-channel protection ratio required is 25 dB, based on the Radio Authority trials made in Essex [Thomas, 2002]. The protection ratio applies to the median-location fields, and assumes that both signals have a location variability of 4.3 dB (rather than the 5.5 dB assumed elsewhere in UK planning).

Prediction of median-time, short-range path loss, as required to determine wanted field strengths, is relatively straightforward. The problem is deterministic to quite a large extent, with bulk losses dependant on major terrain features and statistical treatment required only for local clutter and multipath effects.

The ‘prediction’ of short-term interference over long paths is quite different; even if an accurate model was available that could relate path loss to detailed knowledge of temperature, pressure and water vapour distributions in the atmosphere, the underlying meteorology can only predicted in the short term. Although statistics of path loss tend to show annual trends (e.g. enhanced signals are most common from May to July), the year-to-year variability can be very large.

Nevertheless, a reasonable quantity of data has been gathered (particularly in the 1950’s) on tropospheric propagation at Band III, and much of this data is embodied in ITU-R recommendations. One of these, P.1546, formed the basis for international planning at RRC-06, and is based on sets of curves representing the field strengths to be expected in different environments for different percentage-times.

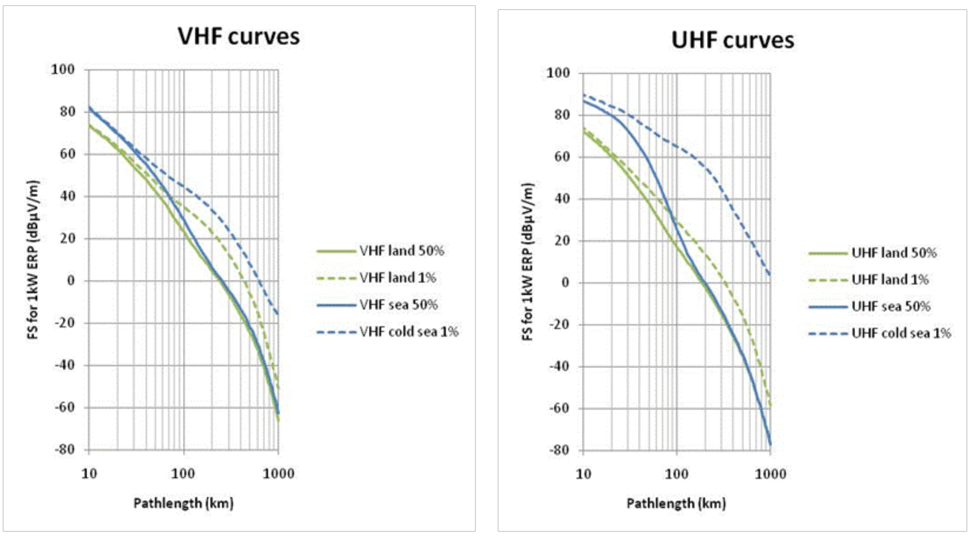

Figure 3.1: ITU-R propagation curves (Rec.P.1546)

These curves show the field strength expected at different ranges, from a transmitter of 1 kW effective radiated power. In the plots given above, the median condition is shown in solid curves, while the short-term (1%) enhanced propagation is shown by the dashed curves. The strength of enhancements over sea paths at UHF can clearly be seen, with signals rising some 30 dB above median levels for 1% time. Luckily for the DAB planner, sea path enhancements tend to be rather less strong at VHF.

A number of questions have been raised regarding the reliability of the data in the ITU-R curves. Some of these concerns relate to corrections that were originally made to the data to render it more representative of 'typical' receiving locations, and to suggestions that weather patterns, and hence interference statistics, have changed over the last half-century. One straightforward criticism, however, is that all the historical measurements were made using transmitters that did not operate during the night (typically, no measurements were made between 23:00 and 09:00, to reflect the hours then in use for broadcasting).

One of the most significant mechanisms for enhanced propagation on land paths is that of 'radiation nights'; when the sky is clear and the air is still, the radiation of heat from the ground at night can cause a temperature inversion in the lower atmosphere, allowing radio ducts to become established. Given the limited hours of measurement, such events would not have been captured in the 1950's data.

3.1 BBC land-path (Daventry) measurements

In the mid-1990's the BBC undertook a long-term measurement campaign to inform the planning of DAB networks and, in particular, to examine the impact of excluding night-time hours from path-loss statistics. In this exercise, signals from five transmitter sites were recorded at a central receiving station for a period of two years. The paths involved, all over land, are indicated in Figure 3.2 below. For one year, measurements were also made at UHF frequencies.

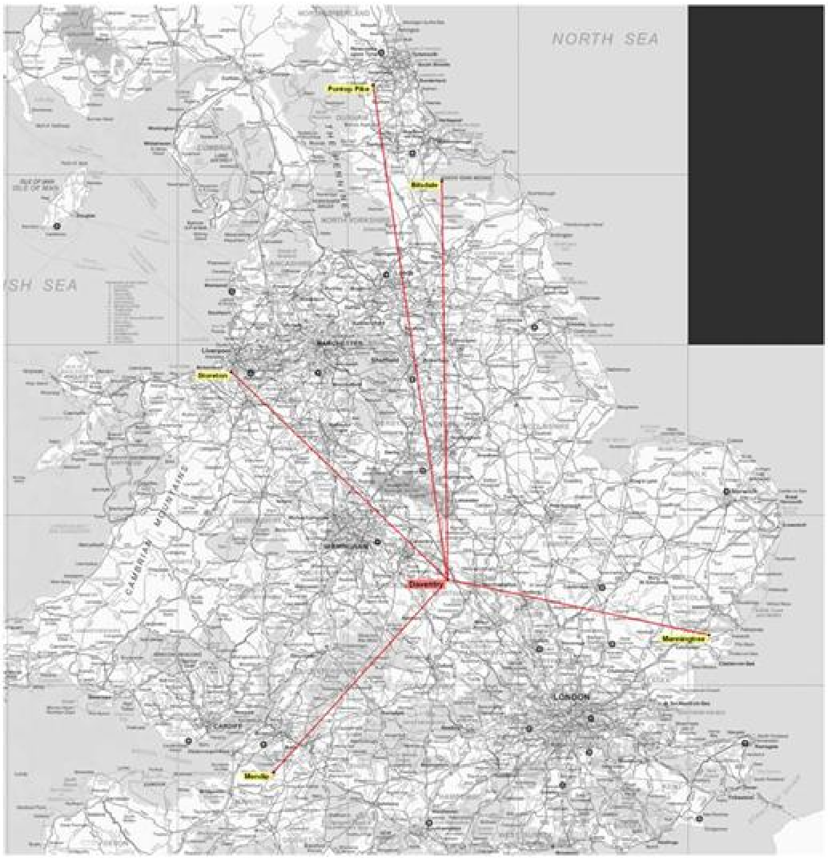

Figure 3.2: BBC land-path propagation measurements

The key findings from this exercise were that:

- Where data was recorded over a 24 hour period, the 1%-time field strengths were found to be around 5 dB higher than when the data was sub-sampled to mimic the restricted hours of the 1950's experiments.
- The 1%-time fields were found to be 13-20 dB higher than predicted by ITU or BBC methods.
- The variability in statistics between the two years was very significant.

Figure 3.3 illustrates the measurements made on one of the longer paths (continuous curves) and compares these to the predictions made by the same ITU-R model that formed the basis[13] of DAB planning at the Wiesbaden-95 and RRC-06 conferences.

[13] The curves of Recommendation P.370 were used in the replacement Recommendation, P.1546.

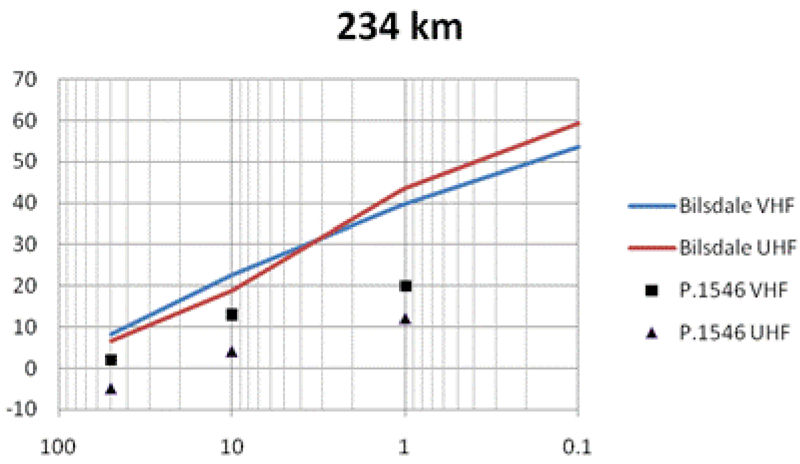

Figure 3.3: BBC measurements compared with predictions

It should be stressed that the results obtained for 24 months of measurement on five UK paths need not invalidate a model that is intended to be generally applicable throughout the world, and is, itself, based on a large database of measurements.

3.2 Prediction algorithms

The predictions algorithms used in the UK for DAB coverage modelling are not in the public domain, but it is understood that they are based on the models developed by the BBC in the 1970's for computer prediction of television service areas, and later adapted for VHF radio planning in Band II [Causebrook, 1978].

In the original BBC algorithms, anomalous propagation is accounted for through large values of modified Earth radius (e.g. multipliers of 4.5 and 25 for 1% time at VHF and UHF respectively). Where a mixed land/sea path exists, a combination of two radius multipliers is used.

Tropospheric ducting is explicitly modelled for sea paths at UHF with a simple empirical expression for sea duct loss. At 1% time, this is:

$$A_T = MAX\left(94.2 \cdot log_{10}\left(\frac{d_n}{383}\right)\right)$$

which sets the ducting loss to zero for paths less than 383 km. No explicit modelling of ducting is used at VHF, or for UHF land paths, beyond the Earth radius multiplier.

The empirical coefficients for the VHF case were set using a total of 86 measurements from longer paths. These measurements would have been the same as those used in the development of the ITU-R models, and made during the limited 'broadcast hours'.

As noted, the exact algorithm used for short-term propagation prediction is not known. It is would be valuable to confirm whether the results of the 'Daventry' measurements have been used to validate or modify the model, and whether any comparison has been made with independent algorithms, such as that of Longley and Rice [Longley-Rice,1968].

Another useful comparison would be with the predictions of the recent ITU-R model given in Recommendation P.1812. This "*path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands*" was developed with significant input from the UK and is intended to be applicable to situations such as DAB coverage prediction. The algorithm for short-term propagation is significantly different to that of the BBC model, and, having originally been developed for UHF and microwave frequencies, required significant modification for use at VHF frequencies.

3.3 Implications for coverage

To highlight the importance of accurate prediction, and of an appropriate choice of the percentage-time for which a network is to be protected, this section gives an illustration of the impact of short-term interference on coverage.

A *hypothetical* DAB service is assumed to be transmitted from the Tacolneston transmitter in Norfolk. It is further assumed that this service is co-channel with the transmitter for a separate multiplex, located on high ground in East Yorkshire, some 150 km away.

In median-time conditions, interference does not degrade the noise-limited coverage area of the Tacolneston service (see Figure 3.4a). For 10% of the time, a few of the original coverage pixels show interference, but, probably, with no significant impact on coverage.

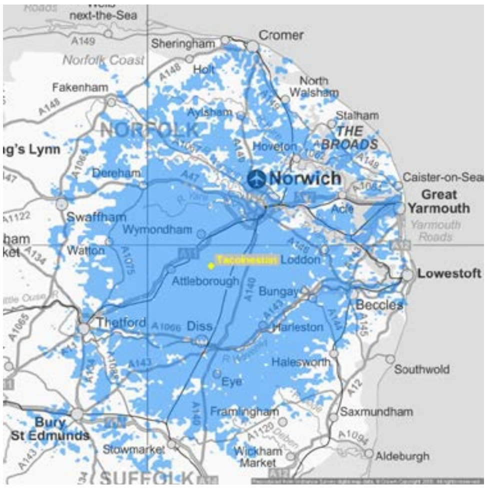

Fig 3.4a: coverage at 50% time

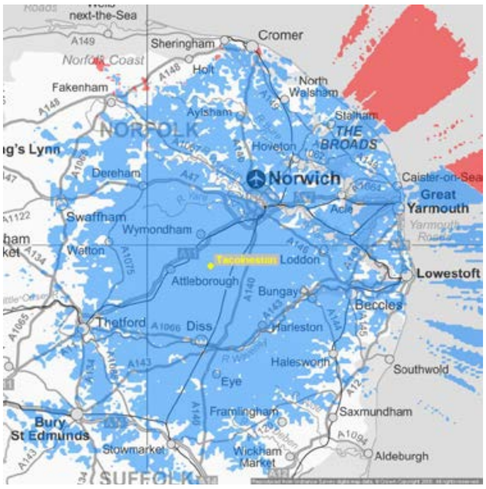

Fig 3.4b: coverage at 10% time

For smaller percentage-times, however, the service shows increasing degradation due to interference from Yorkshire.

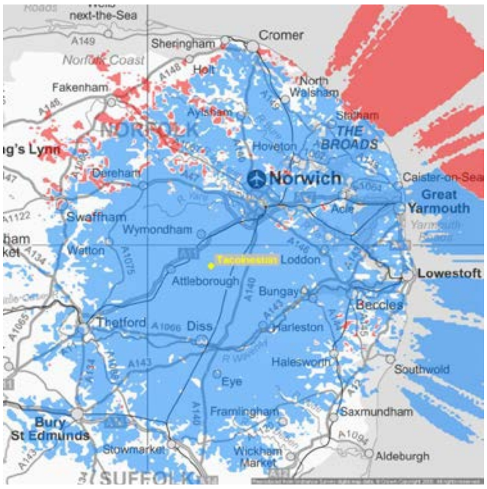

Fig 3.4c: coverage at 5% time **Fig 3.4d: coverage at 1% time**

At 5% time the fringes of the service area are being eroded, but at 1% time the coverage is close to non-existent.

These predictions are made using models that are not optimised for the case of DAB in Band III, and no particular claim is made for their accuracy; they are presented here to highlight the sensitivity of service coverage to small changes in the required availability, and, by extension, to small changes in the prediction algorithms.

In the example above, moving from 5% to 1% has had a dramatic effect on coverage; the fact that these time-percentages are small, however, implies that the models will have been based on relatively little measurement data.

3.4 Discussion

If, as appears to be the case, the existing measurement statistics underestimate the extent of short-term signal enhancement, it is not *necessarily* the case that any changes in prediction or planning should be implemented. It *might*, for example, be judged that if the additional service loss occurs mostly in the early hours of the morning when listening figures are low, it would not be efficient to consume significant resources of bandwidth and money to repair the network coverage. Such judgments are complicated by the great variability of enhancement statistics on daily, monthly and annual scales.

Because (i) small algorithmic changes can have a large impact on apparent service coverage for small percentage times, (2) the sudden, complete loss of digital services is more annoying than the degradation in quality experienced to analogue services and (3) there is some doubt concerning the validity of existing long-path measurement data.

It is recommended that further attention be given to assessing the reliability of short-term interference modelling in DAB networks.

4 PORTABLE RECEIVER PERFORMANCE

4.1 Receiver performance specifications

4.1.1 ETSI

ETSI standard EN 50248 (now renumbered as EN 62104) specifies the minimum performance of DAB receivers.

The sensitivity, defined at a post-Viterbi BER of 10^{-4}, is to meet or exceed −81 dBm measured in a Gaussian channel and −75 dBm in three Rayleigh channels that are specified in the standard. The selectivity should meet or exceed 30 dB with respect to DAB signals in the adjacent channel, or 40 dB with respect to any signals at more than 5 MHz from the wanted channel.

The EN 50248 sensitivity figure is of little value as (i) it is rather un-ambitious and most receivers will easily exceed it by some 15 dB and (ii) it assumes the availability of an external aerial connector.

If a dipole were connected to the input port of a receiver just meeting the specification, it would have a sensitivity of 41 dBµV/m in a Gaussian channel or 47 dBµV/m in a Rayleigh channel.

4.1.2 Expected performance

As noted in Section 1, a number of documents specify the expected performance of DAB receivers.

[BPN-003] derives a minimum required field strength at the receiver of 31 dBµV/m for both car and portable reception. This relates to a Rayleigh channel, assumes an antenna with −2.2 dBd gain (i.e. that of an isotrope) and seems somewhat optimistic.

The Wiesbaden planning meeting [CEPT, 1995] assumed a minimum required field strength at a mobile receiver of 35 dBµV/m in a Rayleigh channel. This figure was adopted in the Geneva RRC-06 planning conference for both portable and car reception.

[TR101 758] derives a sensitivity of 37 dBµV/m for a receiver with a whip antenna of −6 dBd gain operating in a Rayleigh channel. For a Gaussian channel this would correspond to around 31 dBµV/m.

4.1.3 Previous measurements

Results of receiver tests made on behalf of the Dutch Ministry of Economic Affairs are given in an IEEE paper [Schiphorst, 2008].

The gain of three representative whip aerials was measured in an anechoic chamber at the Dutch radio astronomy centre, and a typical gain of −10 dBd was determined (expressed in the paper as ‘a typical antenna factor of 25 dB’).

The remainder of the measurements were made on a sample of 15 receivers. The test set up was fairly sophisticated, using an automated system to detect errors in the audio output of the receivers. All tests, however, were made using a conducted test signal. A diagram shows that the signal generator was connected to the receiver via a 50/75 ohm transformer, but how the physical connection to the receiver was made is not clear. The coupling arrangement used may have had an impact on the apparent sensitivity.

The sensitivity of the test population was found to exceed the EN 50248 limits[14], with the worst 25% of receivers having 6 dB of margin for Rayleigh and Gaussian channels. Nevertheless, when compared with the published sensitivity figures for typical receivers or modules (e.g. −97 dBm), the values of around −87 dBm for a Gaussian channel look rather poor.

Selectivity measurements were also made. For the adjacent channel case it was found that the selectivity measured with an interferer in the upper channel was some 6 dB worse than the lower channel case. For the worst 25% of receivers the 30 dB requirement was not met in the upper channel.

For reasons that are not explained, the authors substituted measurements of the ‘first non-adjacent’ channels in place of the EN 50248 ‘far off selectivity’ measurements (i.e. a separation of 3.4 MHz instead of >5 MHz). These measurements also used DAB signals, in place of the FM carrier specified in the standard. Again, performance was somewhat worse with respect to the upper channel, but fairly poor in all cases. Only the best 25% showed a 40 dB selectivity (incorrectly described by the text as ‘the requirements set by EN 50248’).

4.2 Measurements

As part of this study, a small sample of used DAB receivers were tested in an anechoic chamber at ERA Technology Limited, to determine their sensitivity and selectivity. The measurements focussed on portable receivers with telescopic whips, although the sample included two ‘personal’ radios where the headphone lead is used as an aerial, and a car radio ‘adaptor’ which was tested with alternative aerials —a small magnetically-mounted whip and a stick-on windscreen antenna.

The chamber was set up with a calibrated log-periodic antenna at around 5 m from the device under test. This allowed a known field strength to be established at the DAB receiver location. The onset of impairment (OoI) and point of failure (PoF) were judged by air, using a dielectric acoustical coupler (hosepipe) from the receiver loudspeaker to the engineer running the test.

[14] These are given incorrectly in some of the entries in Table II.

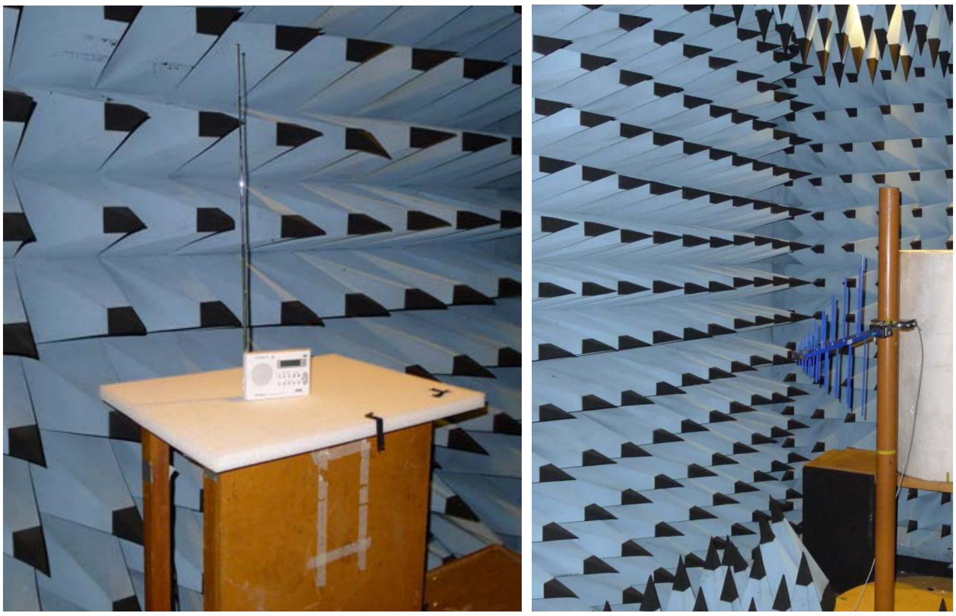

Figure 4.1: Anechoic chamber measurements

It was found that considerable care was necessary to prevent ambient RF energy from coupling into the chamber, which is a Faraday cage apart from a set of cable-entry glands. Although only one cable was penetrating the chamber, and this was loaded with ferrite clamps, the energy from local DAB services was sufficient to distort the sensitivity measurements by up to 20 dB. It was found necessary to locate the signal generators and staff in an adjoining screened room to remedy this interference.

4.2.1 Sensitivity

The plot below summarises the results of the sensitivity measurements.

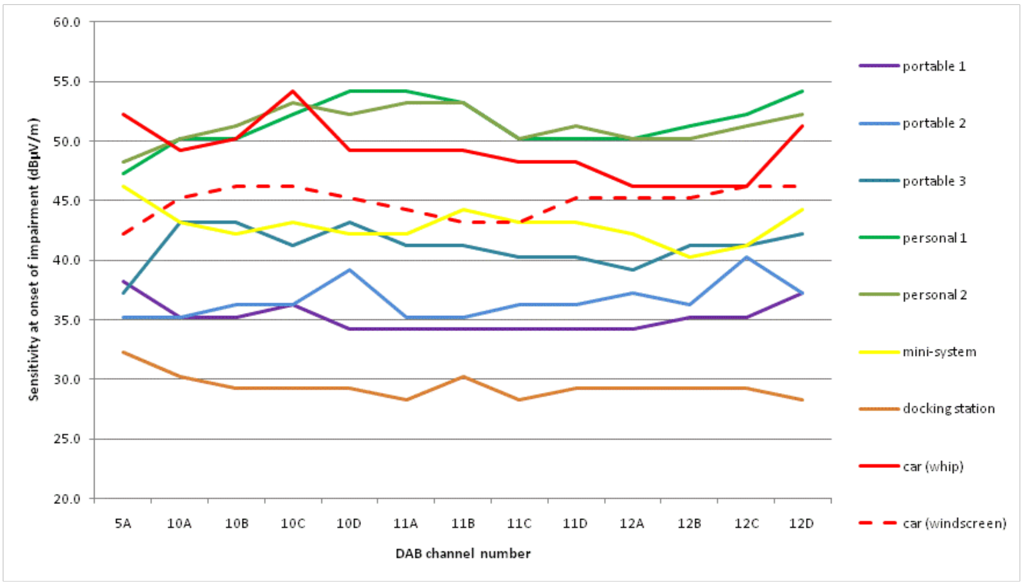

Figure 4.2: Measured sensitivity results

The results show that the worst-performing receivers are, perhaps unsurprisingly, the two ‘personal’ sets, the headphone leads of which might be expected to form relatively poor antennas. A similar performance was given by the small 'mini-system' that has a short trailing-wire aerial.

More surprisingly, the car adaptor showed a somewhat poor sensitivity, and this was most marked when using the whip aerial, which might have been expected to show a better performance than the glass-mounted alternative. The whip was tested on a small (~30 cm) square ground-plane, but when this was substituted with a metal sheet ~1 m square, no improvements was seen.

A small, cheap portable ('portable 3') showed a middling performance, while the two 'typical' portables gave a very reasonable performance working down to a field strength of less than 40 dBμV/m.

The most sensitive receiver was the smartphone 'docking station', which has a trailing wire aerial.

4.2.2 Selectivity

The selectivity of some of the sample receivers was also measured. As noted, the ETSI specification sets requirements for selectivity with respect to a DAB signal in the adjacent channel and with respect to a narrowband interferer at > 5 MHz separation. For the brief measurements carried out in this study, selectivity was simply measured with respect to DAB transmissions offset according to the standard channel raster, as this seems more directly useful than the ETSI requirement.

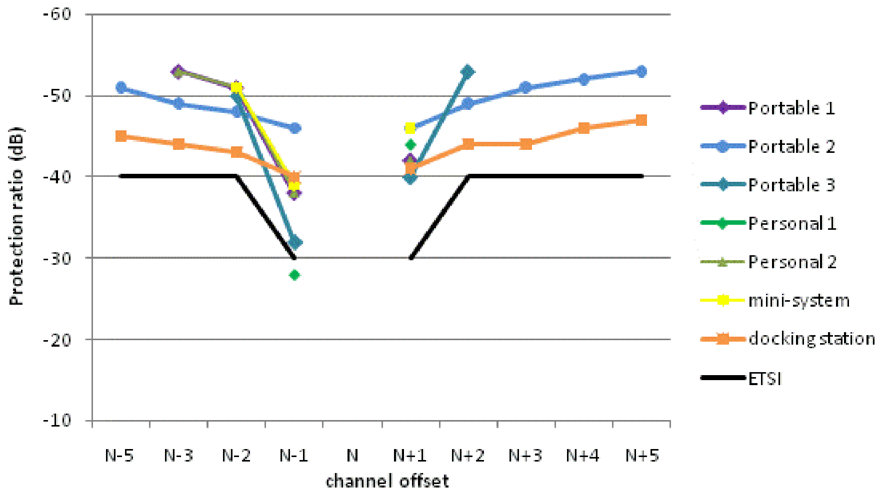

Figure 4.3: Receiver selectivity measurements

The results are shown in Figure 4.3, from which it can be seen that all receivers met the first adjacent requirement (a protection ratio of −30 dB), with the exception of one of the personal receivers. The tendency, noted above in the Dutch measurement [Schiphorst, 2008], for the selectivity to be asymmetrical was also observed, although in these tests the poorer performance was found in respect of interference in the *lower,* rather than upper, adjacent channel.

4.2.3 Commentary

The sensitivity results allow the performance of the antenna systems of these sets to be estimated.

The majority of chipsets on the market claim a sensitivity in the region of −97 dBm for a BER of 10^{-4}. Although not specified, it is assumed that this relates to a Gaussian channel, as was used in the measurements. This would correspond to a sensitivity of 25 dBµV/m if the receiver was connected to a half wave dipole. This suggests that the best set tested here (the docking station) has an aerial system gain of around −5 dBd, which is in line with the suggestions of [TR 101 758].

More typical portable receivers appeared to have an aerial system gain of around −12 dBd, which would imply very poor matching or losses due to other mechanisms. For the worse-performing receivers, it is likely that the additional degradation is due to high levels of receiver self-interference due to noise from control circuitry or other sources. One of the units tested included a note in the manual to the effect that if DAB reception is poor, the CD player should be disabled by following a certain set of key presses on the menu. A brief attempt was made to measure unintentional radiation from some of the worst-performing receivers, but noise floor of the measurement system was too high to allow any firm conclusions to be drawn; it seems possible, in any case, that such self-interference would tend to be coupled by the wiring within the set, rather than being radiated.

These measurements tend to support the current assumption in UK planning of a portable receiver aerial gain of −10.1 dBd.

5 CAR RECEIVER TRIALS

It is simple to determine the sensitivity of car receivers, as a signal can readily be injected into the antenna port. Such measurements have generally been found to reveal a sensitivity of around −95 to −98 dBm for the onset of audible errors. This information is, however, of little direct use in service planning, as the performance of the antenna system is unknown.

Unlike the portable receivers, it will generally not be possible to place a car inside an anechoic chamber (although suitable chambers are used by the automotive and defence industries for EMC testing). Tests have therefore been carried out to estimate car radio sensitivity by means of drive-testing.

In these trials, DAB field strength was measured along a number of routes using a calibrated measuring vehicle. A second vehicle, fitted with a factory-installed DAB radio, was then driven along the same routes, recording the areas in which reception of DAB was intermittent or absent. Combining the results from the two trials allowed an estimate to be made of the sensitivity of the overall DAB receive system in the car.

5.1 Field strength measurement

Field strength measurements were made using a Citroen Picasso vehicle, fitted with a quarter wave whip antenna mounted on a circular ground-plane at 1.7 m above ground level. This installation has been found to give a uniform horizontal radiation pattern.

Figure 5.1: Measurement antenna installation

Three measurement routes were chosen in East Sussex. These routes included river valleys in the South Downs, including areas known to suffer poor reception of the local ‘Sussex Coast’ multiplex on channel 11B.

The predicted coverage[15] of this multiplex is indicated in Figure 5.2, with the most significant contributions coming from transmitters at Whitehawk Hill, Beddingham and Hastings, with some additional coverage from a low-power site at Eastbourne. Field strengths above 64 dBμV/m are coloured green, 58–64 dBμV/m blue and 52–58 dBμV/m pink.

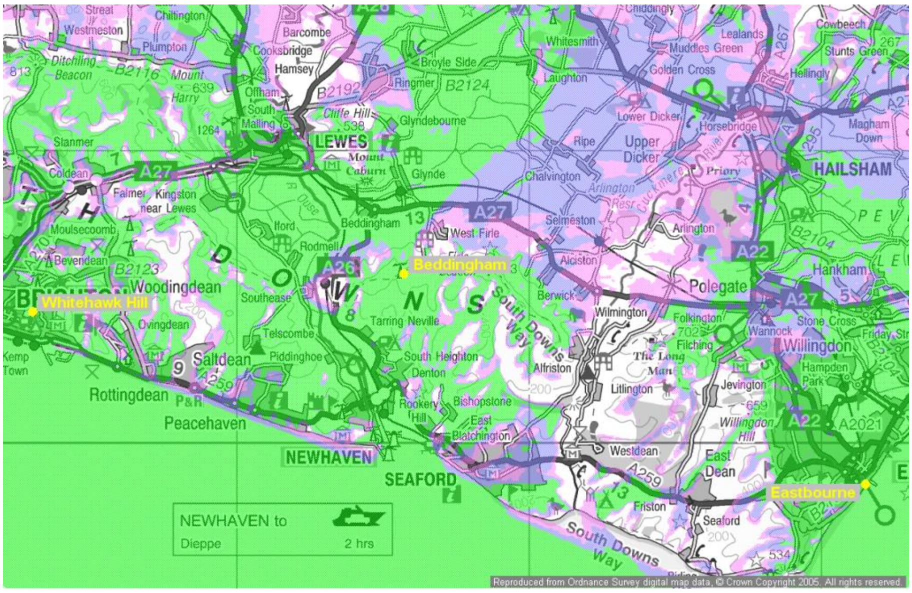

Figure 5.2: Predicted coverage of Sussex coast multiplex

The measured field strength is shown in Figure 5.3.

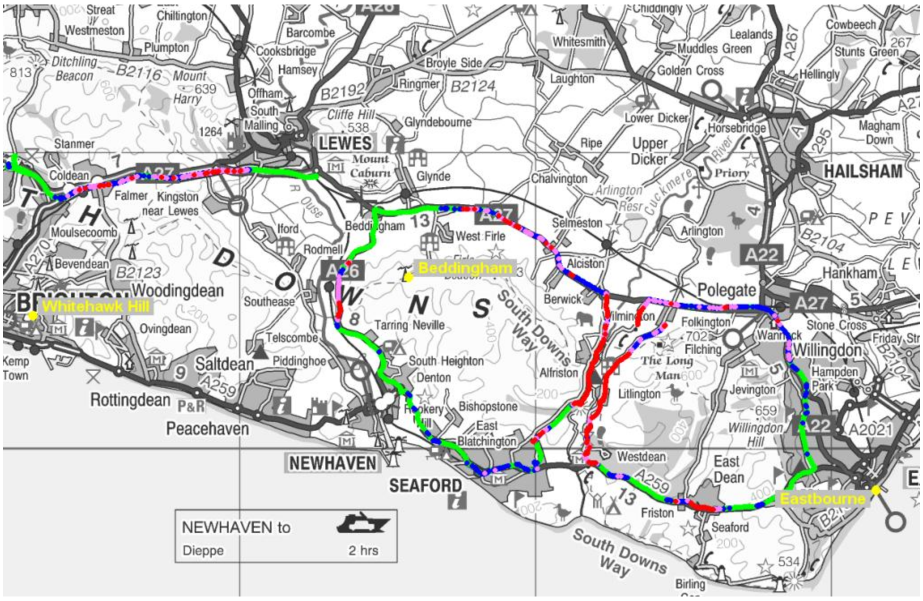

Figure 5.3: Predicted field strength of Sussex coast multiplex

In Figure 5.3, the same colours are used as in Figure 5.2, but with a 13 dB allowance for height loss; fields above 51 dBμV/m are therefore coloured green (red

[15] Predicted using Aegis software tools.

points correspond to fields below 39 dBµV/m, which are uncoloured in the prediction).

It can be seen that there is a fairly close correspondence between the prediction and the measurements.

5.2 Interference

The Sussex coast multiplex is currently co-channel with the 'London 3' multiplex, and is interference-limited in many places as a result. A coverage prediction was made taking this interference into account (Figure 5.4). Areas coloured blue receive median field strength above 52 dBµV/m[16] at 10 m with an adequate protection ratio; areas coloured red have sufficient field strength but are limited by interference for 1% time.

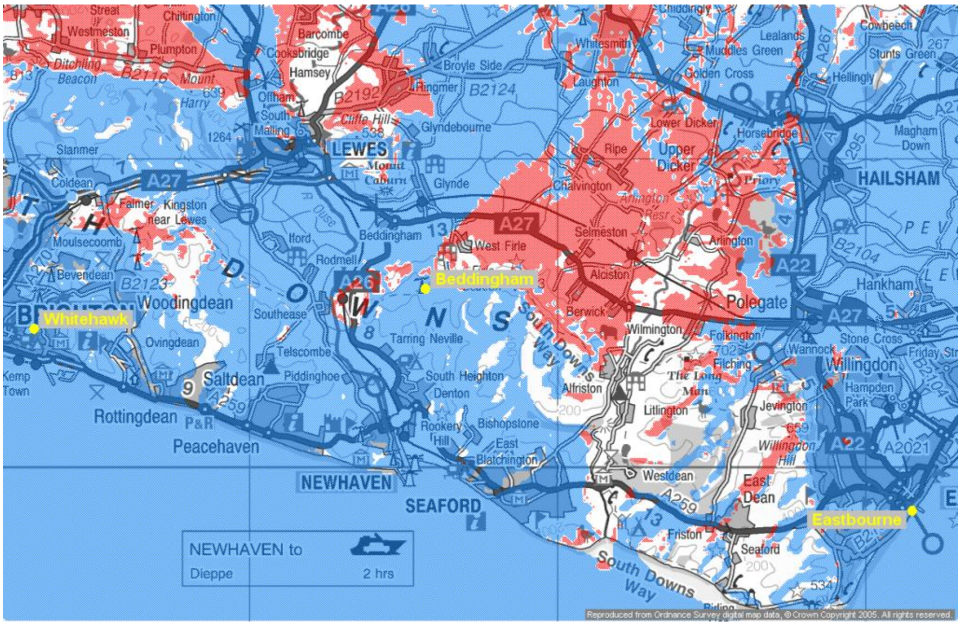

Figure 5.4: Interference-limited coverage of the Sussex Coast multiplex

It is necessary to understand the interference environment when assessing the car receiver sensitivity, as coverage deficiencies may be due to high levels of interference rather than a lack of wanted signal; if this were not recognised, a pessimistic estimate would be made of the receive antenna system gain.

5.3 Assessment of car receiver sensitivity

A new family saloon car, factory-fitted with a DAB radio, was made available for these tests by a local dealer[17]. The antenna was of the 'bee-sting' type, mounted at the rear of the roof, and it seems likely that it is an active antenna with a preamplifier in the base of the unit.

[16] This criterion was chosen, somewhat arbitrarily, as initial measurements showed that the sensitivity of the car receiver was such that reception should be possible below the 58 dBµV/m planning limit.

[17] The project team are very grateful to the Birchwood Motor Group for their assistance with these tests.

Figure 5.5: Showing factory-fitted car antenna

The car was driven around the routes indicated in Figure 5.3. As no direct connection was possible to the car receiver, a video camera was used to record both the audio from one of the services on the multiplex (BBC Radio Sussex), and the view through the windscreen. This allowed post-processing to establish the locations of service failure with good accuracy.

It was found that, in areas where no co-channel interference is predicted, good reception was possible for median field strengths down to around 38 dBμV/m. If a height gain figure of 13 dB is assumed, in line with [BPN-003], this would imply a noise-limited coverage limit for mobile reception of 51 dBμV/m at 10 m. This is a significantly better figure than the 58 dBμV/m figure currently assumed for planning.

During these measurements, a second saloon car from a different manufacturer, and also with a factory-fitted DAB radio, was driven along the same routes by an Ofcom staff member; an informal comparison indicated that the overall sensitivity of the two vehicle systems was very similar, with loss of service occurring in near-identical locations.

Although only a single, brief, trial has been made, these results would seem to suggest that the sensitivity of factory-fitted DAB car radios is unlikely to constrain the coverage achieved in practice. As a consequence, the service area of many multiplexes may be limited by co-channel interference rather than by noise.

6 RECEIVER DEVELOPMENTS

6.1 Receiver architecture

The traditional form of radio receiver uses a superheterodyne architecture, in which signals received at the broadcast frequency are mixed with a variable local oscillator to transform them to a fixed 'Intermediate' frequency (IF), at which most of the filtering and gain can be implemented, prior to demodulation. The IF is chosen to be a compromise between a frequency low enough to allow amplifiers and (more importantly) filters to be realised easily, but high enough to avoid so-called 'image channel' interference problems.

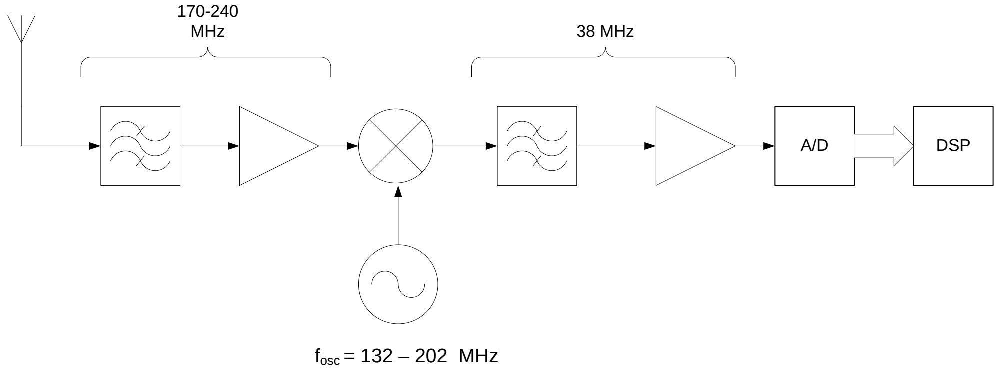

Figure 6.1: Traditional superheterodyne architecture

For the example in Figure 6.1, a desired signal at 222 MHz is translated to 38 MHz when the local oscillator is tuned to 184 MHz. A frequency at 146 MHz would also, however, be translated to the same IF, and any local signals at this second frequency could cause interference to the wanted signal.

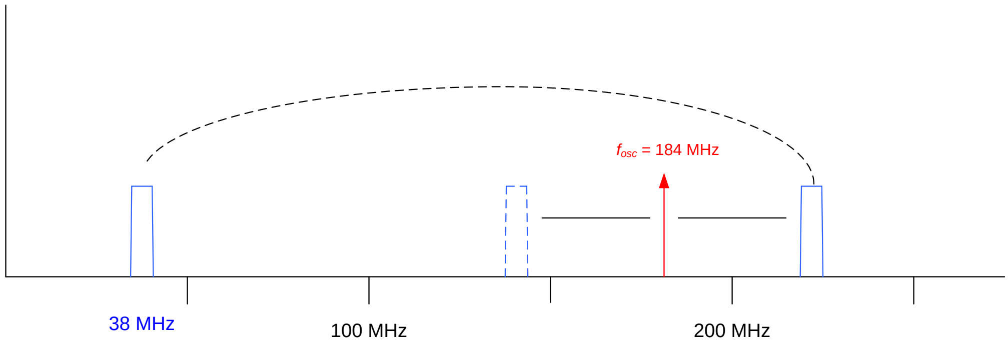

Figure 6.2: Frequency relationships in traditional superhet

In practice, it is relatively easy to protect against such interference using the first bandpass filter shown in Figure 6.1. As there is a 76 MHz difference between the wanted and image frequencies a simple filter could provide considerable attenuation of any interference. In some designs this item might be a fixed filter with a passband wide enough to accept any frequency in the tuning range of the receiver, while in other cases it may be a narrowband filter with varactor diodes tuned by the receiver control logic.

The first generation of professional and consumer DAB receivers, based on the so-called JESSI chipset, used this approach. Although simple, and offering high performance, the scheme does not lend itself to integration in silicon or CMOS. The necessary RF and IF filters require lumped components, and a further frequency conversion is generally necessary to avoid the need for an ADC with an expensively high, power hungry, sampling frequency.

These problems can be overcome by using the ‘direct conversion’ architecture, shown in Figure 6.3. In this scheme, the local oscillator frequency is the same as the signal frequency, so that the wanted signal is translated directly to baseband.

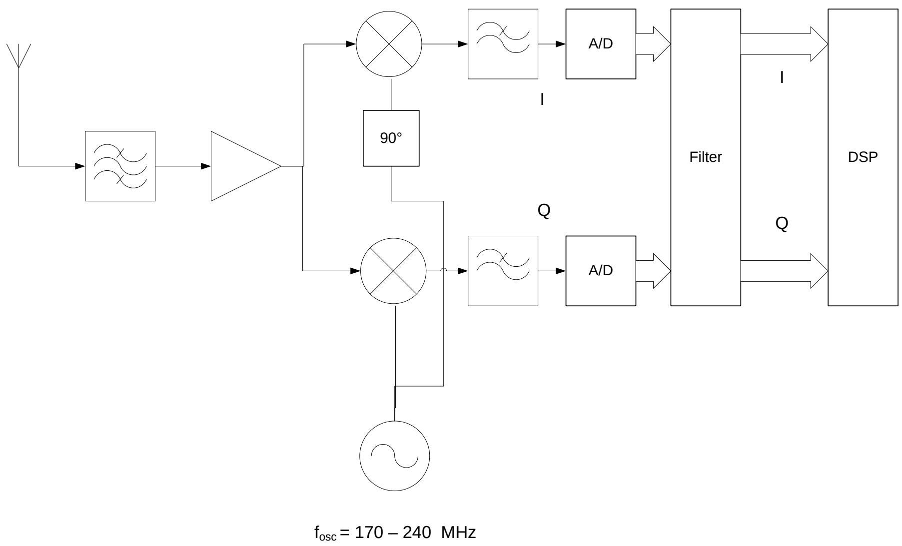

Figure 6.3: Direct conversion architecture

There is now no image response (the ‘image’ can be considered to be the wanted signal itself, inverted around the zero-frequency axis, as shown in Figure 6.4), and RF filtering requirements can therefore be considerably reduced. Furthermore, the ADC is only required to operate at baseband frequencies and accurate channel filtering can readily be implemented in DSP, allowing a very integrated design with a minimum of off-chip components.

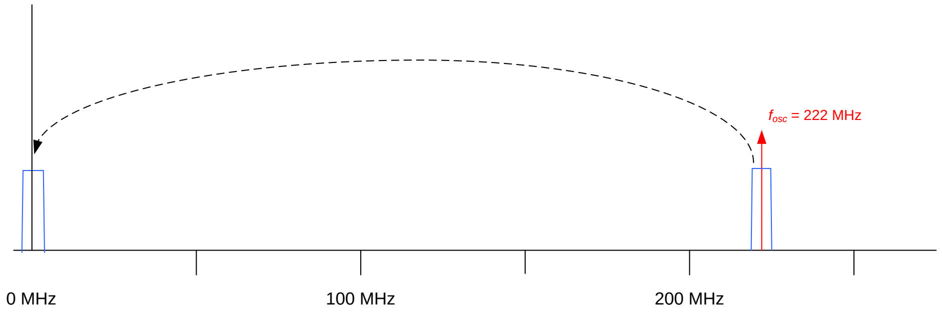

Figure 6.4: Direct conversion frequency translation

This approach has some significant disadvantages, however. The ADC must have a large dynamic range or careful analogue filtering and gain control to accommodate potentially large powers from adjacent and out-of-band signals, the quadrature relationship of the two channels requires very accurate calibration for good performance, and leakage of the local oscillator, which is translated to zero-frequency, can lead to problems of DC balance. Furthermore, 'flicker', or '1/f' noise generated by current flow in resistors and semiconductor junctions can become a limiting performance factor at the low frequencies at which most gain is realised.

Despite these potential problems, direct conversion receivers are popular in applications such as wireless LANs, where the wide bandwidth makes the flicker noise issue less important; the 802.11 standard accommodates direct conversion receivers by suppressing the centre carrier to simplify DC balance issues (similarly, the DAB centre carrier is unmodulated).

Because of the physical size and cost constraints inherent in the superhet architecture, and the problems associated with 1/f noise, an alternative approach, using a 'near-zero IF' has been adopted for the majority of DAB receivers currently on the market.

This architecture has characteristics of both the other approaches, with the signal frequency being translated not to zero frequency, but to a position that allows the lower edge of the wanted channel to sit slightly above DC. This allows the use of an ADC with a low sampling frequency (for low power consumption), but avoids the worst impact of flicker noise.

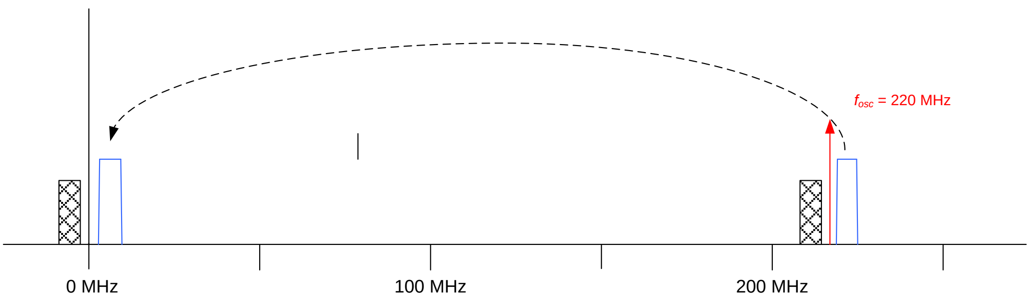

Figure 6.5: Near Zero IF frequency translation

The image channel (shown hatched in Figure 6.5) now falls very close to wanted channel, and will typically be an adjacent channel of the same system. This makes the interference environment more predictable, and may reduce the performance specification that must be met (in the DAB case, a traditional superhet will need to reject an image channel by 40 dB, whereas an NZIF receiver will only need to achieve 30 dB, according to the requirements of [EN 50248].

Implementing a filter to remove this image requires new techniques, however, because the unwanted signal falls on frequencies that, in a real number representation, would be folded around zero-frequency to lie top of the wanted signal. A complex 'polyphase' filter allows different responses to be created for positive and negative frequencies (i.e. for different directions of phasor rotation), allowing the negative 'image channel' to be rejected.

One possible receiver architecture is shown in Figure 6.6. In this arrangement, the complex filter is implemented digitally after the ADC. This arrangement allows excellent and repeatable filter characteristics to be implemented, though the penalty is that the ADC must have a sufficient dynamic range to cater for the potentially large unwanted signal. In Figure 6.6 the final conversion to baseband is also achieved in the digital domain.

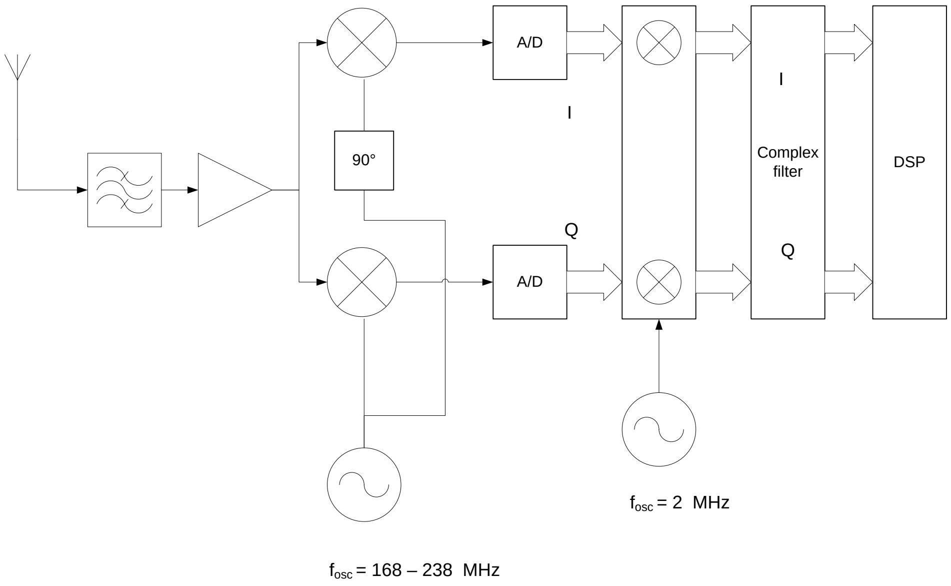

Figure 6.6: Near-zero IF architecture

An alternative arrangement can be seen (Figure 6.7) in a design by Frontier Silicon, in which an analogue filter precedes the ADC (which resides on the associated baseband chip). In this design, the NZIF is at 1.024 MHz, and the filtered signal is then upconverted to a standard interface IF of 2.048 MHz for consumption by the ADC.

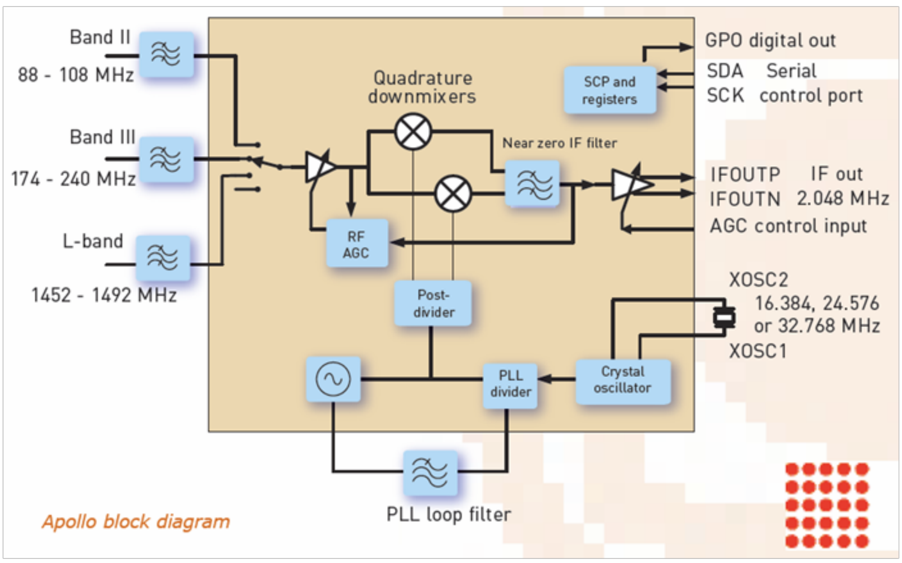

Figure 6.7: Frontier Silicon 'Apollo 1' RF chip design (www.frontier-silicon.com)

The Frontier Silicon design also illustrates the use of separate chips for the RF and baseband processing functions. While CMOS technology allows the rapid switching and low power consumption required for the realisation of complex digital processors, it is less well adapted for low-noise analogue use than Silicon and Germanium (SiGe) implementations[18]. In applications where size is of paramount importance (e.g. mobile phones) single chip solutions may be used, with some compromise to performance.

6.2 Sample receiver implementation

An inexpensive (£35) receiver was purchased from a supermarket, with the aim of examining the details of the RF implementation.

Figure 6.8: Sample receiver

The unit covers Band III DAB and Band II FM. Somewhat surprisingly, it uses a rather generous 6 x AA alkaline cells as the power supply, giving a 9 V supply rail. The supplied mains adaptor, however, is rated at 7.5 V, so it may be that the battery count is intended to allow the use of rechargeable cells, though this is not mentioned in the manual.

The receiver was dismantled to reveal a circuit board supporting power supply and audio components, a display module and a receiver module. The telescopic aerial is connected to the receiver module by a length of equipment wire. When the aerial is fully extended the whip (50 cm) and connecting wire together have a length of 62 cm, equivalent to 0.46λ at 222 MHz. If such a length was extended normal to a ground-plane, the receiver module would 'see' an inductive source with a rather high resistive component, perhaps around 200 + J300 Ω. In practice, no attempt has been made to engineer any form of counterpoise or ground-plane, so all that can be said is that the aerial impedance is likely to be high and inductive.

[18] It should be noted that Frontier silicon do not specify the processes used in their RF and baseband chips.

Figure 6.9: Internal construction of receiver

The receiver module was examined in detail (Figure 6.10), and *appears* to the Venice 7 module from Frontier Silicon (though there is no branding on the unit).

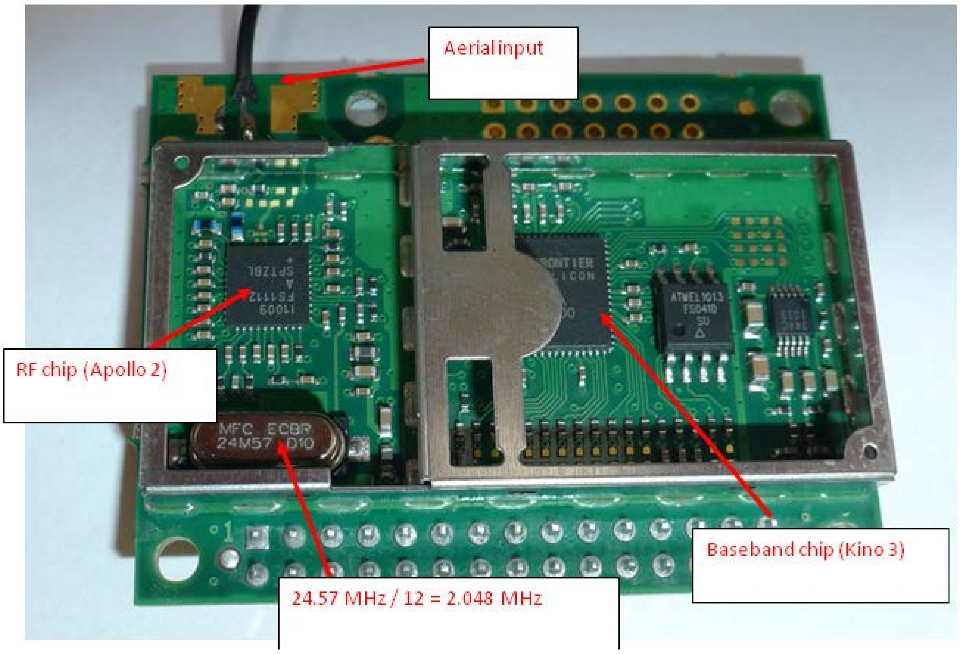

Figure 6.10: Elements of DAB receiver module

The aerial lead is soldered to the pad that would normally accommodate the centre conductor of an SMA connector, with no additional matching. Within the module, the 'Apollo 2' front end and the 'Kino 3' baseband chip are visible. The latter supports DAB, DAB+ and DMB, as does the standard Venice 7 module. These options do not appear to be enabled in the firmware of the sample receiver, and there is no interface adaptor to allow upgrades to be imported.

The maximum voltage required by the module is 3.3 V, which makes the use of six cells in the receiver more surprising.

The specified ('typical') sensitivity of the module in DAB/DAB+ and DRM modes is −100 dBm. If a properly matched dipole antenna were connected to the module, this would imply a sensitivity in terms of field strength of 22 dBμV/m.

As has been seen from the measurements reported in Section 4, the best performing receivers have a sensitivity of around 30 dBμV/m, implying an aerial system gain of around −8 dBd (or −6 dBi).

The opportunity was taken to measure the sensitivity of the receiver and, rather to the surprise of the author, this was found to be around 26 dBμV/m for the onset of impairment. This figure makes the receiver more sensitive than any other unit tested, and suggests that the antenna arrangements are 'appropriate' engineering[19]. It also suggests that the lower sensitivity seen from similar units is likely to be, at least partly, due to high levels of self-generated noise.

6.3 Discussion

The design of DAB receivers has evolved substantially over a period of some 15 years, from traditional superhet devices with an adjacent channel response defined by a SAW filter, image channel rejection given by a tracking filter constructed from discrete components, and a discrete FET low noise amplifier at the front end.

A typical modern receiver uses a near-zero IF architecture, in which adjacent channel (which is the same as image channel in this architecture) selectivity is provided by low frequency analogue or digital polyphase filters with stable characteristics. The first active device will be integrated on the chip. If separate chips are used for the front end and for baseband processing, the thermal noise performance is unlikely to limit the performance of the overall radio. If a single chip CMOS solution is adopted to minimise size or cost, there may be a penalty both in terms of noise and strong-signal handling.

The market for Eureka 147 compliant devices is currently expanding with the adoption of DMB in France and DRM+ elsewhere in Europe and Australia. Most, if not all, chipsets currently being produced are capable of decoding all three standards, so the inclusion of the functionality in the finished product is, essentially a marketing decision. This being the case, it is unfortunate that, although receivers, such as the sample examined above, include the hardware necessary to decode DRM+, this is not enabled. This presumably reflects IPR issues, but is serving to

[19] When the receiver was modified to include a tinplate ground-plane and a properly matched whip antenna, the sensitivity remained unchanged.

entrench the existing UK standard as the population of DAB-only radios continues to grow.

Although there seems to be a contrast between the sophistication of the engineering design incorporated in DAB receiver modules and the relative crudity of the antenna arrangements in the devices in which they are integrated, this does not seem to have an impact on the performance. More serious may be issues relating to the internal EMC of devices, as it seems likely that locally generated noise establishes the usable sensitivity of many receivers.

7 CONCLUSIONS

This brief study has examined a number of aspects of DAB coverage planning. The following headline observations have been made:

- On the basis of a few reported results, and the present measurements, the −2 dBd figure assumed for aerial system gain in cars and portables at the planning conferences and in [BPN-003] may be optimistic. The UK assumption of −5 dBd seems appropriate.
- The generally-assumed location variability of 5.5 dB does not seem to be well-supported by reported measurements, which suggest a lower figure. The good coverage obtained for relatively low median signal strengths in the drive test measurements would tend to support this assertion.
- There is an arbitrary element to the values that have been assumed in the various reference documents for receiver C/I requirements in a Rayleigh fading channel. Some of the adopted values do not correspond to the results of laboratory measurements. Equally, the fading models used in the laboratory measurements (from COST 207) do not seem to have been shown to apply for Band III DAB reception.
- Assumptions for height gain between 1.5 m and 10 m vary in the range 10–13 dB. Though these values seem plausible, they do not appear to be linked in any reliable way to valid statistical data.
- The 8–9 dB given for median building penetration loss in some reference documents may be rather low if coverage is required to the ground floor of traditional, especially commercial, buildings in dense urban areas. The UK planning assumption of 8 dB for suburban areas and 15 dB in dense urban areas seems appropriate.
- Although individual elements of the link budget may be uncertain, the planning limit of 58 dBμV/m for mobile coverage seems appropriate in the light of the brief measurements made in this study.
- The revised planning criteria for indoor coverage, described in Section 1.2, seem appropriate in the light of the review of building loss measurements (section 2.7) and the receiver performance measurements (section 2.4).
- It has not been possible in the timescale available for this work to establish exactly what assumptions are currently made in predicting levels of short-term interference. The accurate statistical prediction of such interference, and the relationship with subjectively perceived network performance, is probably the single most important factor in efficient network planning, and may warrant further study.

A REFERENCES

NB: Where document numbers, e.g. BPN 003, are familiar to those working in the area, they are used as references instead of the usual format of [author, date].

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[BS.1203-1] "*Digital sound broadcasting to vehicular, portable and fixed receivers using terrestrial transmitters in the UHF/VHF bands*", ITU-R Recommendation BS.1203-1, Geneva, 1994.

[BS.1660-3] "*Technical basis for planning of terrestrial digital sound broadcasting in the VHF band*" ITU-R Recommendation BT.1660-3, Geneva, 2006.

[BT.1368-6] "Planning criteria for digital terrestrial television services in the VHF/UHF bands", ITU-R Recommendation BT.1368-6, Geneva, 2006.

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[Maddocks, 1993] Maddocks M. C. D and Pullen, I. R., "*Digital Audio Broadcasting: comparison of coverage at different frequencies and with different bandwidths*", BBC Research Department Report RD 1993/11.

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[Schramm, 1997] Schramm, R., "*Pseudo channel BER—an objective quantity for assessing DAB coverage*", EBU Technical Review, Winter 1997.

[TR 101 758] "*Digital Audio Broadcasting (DAB); Signal strengths and receiver parameters; Targets for typical operation*", Technical Report TR 101 758 v.2.1.1 ETSI, Sophia Antipolis, 2000.

B DETERMINATION OF C/N REQUIREMENTS

B.1 Gaussian channel

An early (1994) ITU-R recommendation [BS.774-1] refers to measurements[20] made using a data channel with a bit rate of 64 kbit/s and a 0.5 code rate. For a post-Viterbi bit-rate of 10^{-4}, a C/N of **7.1 dB** was found necessary, compared with ~6.6 dB value derived from simulation. In the next revision (1995), at which the material was moved to a different recommendation [BS.1114-1] the corresponding results are **7.6 dB** (measured) and 6.7 dB from simulation, apparently for the same conditions.

An EBU document [EBU, 95] prepared in advance of the Wiesbaden (WI-95) planning meeting gives a single value of **7 dB** for the Gaussian channel C/N requirement. This value appears to be based on the measured 7.1 dB value quoted in [BS.774-1] and [BS.1203-1]. The 'Technical bases' that appeared as Annex 2 of the Final Acts of the meeting [CEPT, 95] did not identify C/N values explicitly, but the field strength values are clearly based on the same assumptions.

Measurements [Gilchrist, 94] at PL3 and 192 kbit/s found that a third-generation receiver required a C/N (at onset of impairment) of between **6.5–8.0 dB**[21] in a Gaussian channel. Later tests [Gilchrist, 96] on a fourth-generation receiver gave very similar results (**6.5–7.5 dB** for OoI, at 224 kbit/s). The values for complete failure were 2–3 dB lower.

BPN 003 states that *"for a Gaussian channel a C/N value of 7.4 dB is required for all four transmission modes to achieve a Bit Error Ratio (BER) of 1 x 10^{-4} after Viterbi".* The text implies that this value relates to PL3 and derives C/N values for the other protection levels by means of a comparison with the performance of DVB-T. It is not clear to the author that this is a particularly rigorous procedure, although the results are likely to be of the right order.

[BPN 003] also asserts that "*Section 10.1 of Rec. ITU-R BS.1114 contains data on the performance of DAB in a Gauss channel. For Band III, a C/N ratio of 7.4 dB is required for a BER of 1x10^{-4}, assuming protection level 3*". This is not, however strictly correct. In fact, this section the Recommendation (in all revisions) includes two graphs—that relating to Modes II and III does indeed show a C/N of 7.4 dB at a BER of 10^{-4}, but the plot for Mode I shows a value closer to **7.6 dB**, as noted above.

In section 10.4 of [BS.1114] values of S/N versus subjective sound quality are presented, apparently based on [Gilchrist, 1994]. Very similar values are reported in [ETSI 101 758].

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[20] The same measurements are also reported in Annex 1B of ITU-R Report [BS.1203-1] of 1994.

[21] The spread in values reflects the uncertainty in subjective assessment, and the differences between programme material.

ETSI TR 101 758 reproduces (as figure 1) the same plot[22] for Mode I performance given in BS.1114 which shows a value of 7.6 dB for BER=10^{-4}. The text simply notes the variability of this figure with mode, protection level and experimental arrangement, as summaries required Gaussian C/N as 'about 8 dB and 6 dB' for threshold of audibility and failure respectively. The document does not use the Gaussian value further, as coverage targets are based on the Rayleigh values.

B.2 Rayleigh channels

While the performance in a Gaussian channel is straightforward to measure, and provides a simple metric for the comparison of receiver sensitivity, it is an inadequate basis for service planning. Very few real-world channels will appear Gaussian, with the possible exception of those to fixed receivers using a rooftop aerial system.

For the case of a portable or car receiver, it is likely that no direct line-of-sight signal will exist, that multipath will be present and, if the receiver is in motion (or objects around it are) the received signal will suffer Doppler spread.

All the documents mentioned above therefore include figures for receiver performance in more complex channels, and it is these figures that have been used to define coverage limits.

B.2.1 BS.774 / BS.1114

The first measurements reported (in BS.774-1) relate to Mode 1, and a data channel (bit rate of 64 kbit/s, code rate = 0.5). A fading channel simulator was used with three profiles; rural with a receiver speed of 130 km/h, a 'highly dispersive' urban channel at 15 km/h and for an extreme SFN example with active echoes at up to 600 μS delay and a speed of 130 km/h. No further details of the channels are given. For BER=10^{-4} the 'rural' channel required C/N=15.2 dB, the 'SFN' channel 15.0 dB and the 'urban' channel 14.1 dB. A software simulation was also run for the rural case, giving a result of 12.5 dB, implying an implementation loss of ~2.7 dB.

In the updated version of the Recommendation (i.e. BS.1114-1), further fading simulator measurements are reported, using profiles explicitly identified as those from COST 207. Measurements are again made at 64 kbit/s, CR=0.5 but, additionally, at 24 kbit/s, CR=0.375. The C/N requirements are as indicated in the table below, and the same results are included in ITU-R Report BS.1203.

[22] Giving as the source ITU-R Special Publication: "Terrestrial and satellite digital sound broadcasting to vehicular, portable and fixed receivers in the VHF/UHF bands, Geneva, 1995".

Table B.1: Fading channel C/N requirements for BER 10^{-4} (BS.1114-1)

COST 207 profile	CR = 0.5	CR=0.375
Rural (130 km/h)	15.4 dB	12.7 dB
Urban (15 km/h)	11.8 dB	9.8 dB

This version of the Recommendation also summarised measurement results which appear to be the same as those reported in [Gilchrist, 1994]. The results, for Band III, Mode 1, CR=0.5 are reproduced in Table B.2.

Table B.2: Fading channel C/N subjective requirements (BS.1114-1)

	Onset of Impairment	Failure
Rural (130 km/h)	17.6 dB	10.0 dB
Urban (15 km/h)	16.0 dB	9.0 dB

These results would suggest that the 'Onset of Impairment' occurs some 2 dB before the 'BER=10^{-4}' point, which, in turn, is some 3–5 dB above the point of failure.

B.2.2 Wiesbaden (WI-95) and Geneva (GE-06) plans

Prior to the planning meeting, document [EBU, 1994], C/N values of **15 dB** and 14 dB are assumed for the rural (130 km/h) and urban (15 km/h) cases respectively, with the larger value used to derive the minimum median field strength used for planning (58 dBμV/m at 10 m agl). In the Final Acts the same values are assumed, though not made explicit.

The technical planning within the RRC-06 process assumed [ITU, 2006] the same C/N value of 15 dB, which is said to be *"… derived from Recommendation ITU-R BS.1660-2*". This Recommendation does not, however, include the 15 dB figure, nor does it give any other information that might be used to derive it.

B.2.3 BPN-003

In annex 2 of this document, it is stated that BS.1114 "… *contains data on the simulated performance of T-DAB in one out several possible Rayleigh channel profiles"*. It would, perhaps, be more accurate to say that the Recommendation contains data on the <u>measured</u> performance of T-DAB in one of several <u>simulated Rayleigh channels</u>. It quotes a figure of 14.8 dB which, however, does not appear in any version of BS.1114, and remarks that this is much greater than a value derived with reference to DVB-T performance. The document then asserts that experience suggests "*… that a C/N value between 13 dB and 13.5 dB seems more appropriate*". This reduced value is then used to 'derive' a required Rayleigh C/N of 13.3 dB.

In the body of the document, the 13.3 dB figure for PL 3 is tabulated, but in the derivation of minimum median field strength for portable and mobile reception, a value of **13.0 dB** (i.e. an uplift of 5.6 dB with respect to the Gaussian figure) is "considered to be representative".

It must be concluded that the planning values given in BPN-003 are based on assertion (which may be perfectly valid), rather than any rigorous derivation.

B.2.4 TR 101 758

In [TR 101 758] the same results as in BS.1114 are given (as in Table B.1 above), showing the results of measurements made on DAB system performance for a number of different simulated propagation channels.

The Document then states that "*most broadcasters accept that the most extreme conditions that the system should be expected to work* (sic) *is that described as 'URBAN*", and proposes a C/I target of **14.0 dB** as '*an appropriate compromise*'.

No rigorous justification, in terms of the impact on coverage, is given. At a code rate of 0.5 (protection level 3) the adoption of the criterion would imply that some fast moving receivers in rural areas will not be served, if it can be assumed that the simulated Rayleigh channel is representative of the real-world case.

B.2.5 Measurements of fading DAB channels

There is little direct evidence on which to base the modelling of the wideband DAB mobile channel. What would be required is a systematic statistical measurement survey of wideband channel statistics in realistic environments, and the author has found no evidence that such work has been undertaken.

The BBC did record DAB channel impulse responses in some early trials, though these only involved the capture of scalar time-domain data and were at UHF [Shelswell, 1991]. A sample impulse response from a dense urban area is shown in Figure B.1.

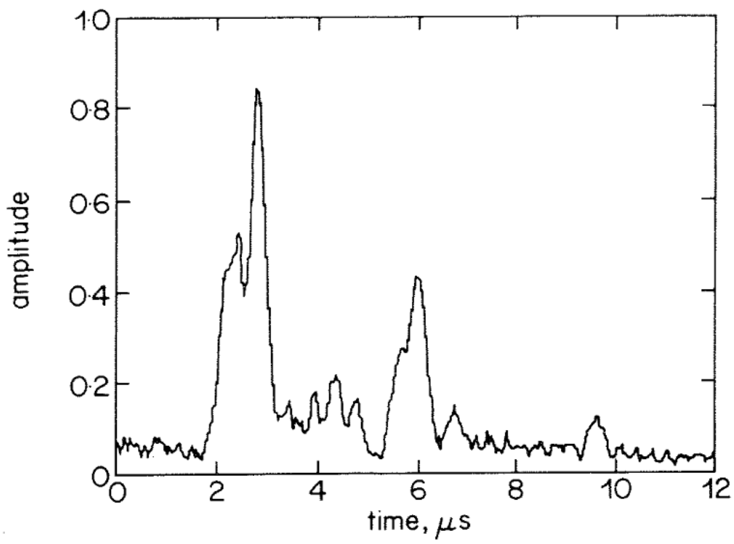

Figure B.1: Measured delay profile (531 MHz) in dense urban area (BBC)

Figures 7.2 and 7.3 in [Hoeg, 2003] show channel scattering diagrams, but their derivation is not made clear. It is possible that they may not even relate to DAB systems. In any case, the interpretation in the text relates to 1.5 GHz.

The measurements reported in [Gilchrist, 1994] and [Gilchrist, 1996] made use of standard channel profiles simulated using the Grundig ‘FADICS’ equipment. These profiles appear to be those defined in the COST 207 project for use by the developers of GSM mobile systems operating at 900 MHz. It is not clear to the author whether their use at 200 MHz has been justified in any formal sense.

Annex B of [EN 50248], which specifies the fading models to be used in receiver testing is taken almost directly from [COST 207], but specifies only two of the four profiles given in that document, the Rural Area (RA) and ‘Typical Urban (TU) models. In addition to these COST 207 profiles, a DAB-specific profile is defined, to mimic the environment seen in SFNs. The simulated vehicle speed to be used with each profile is specified in Table 2 of the document.

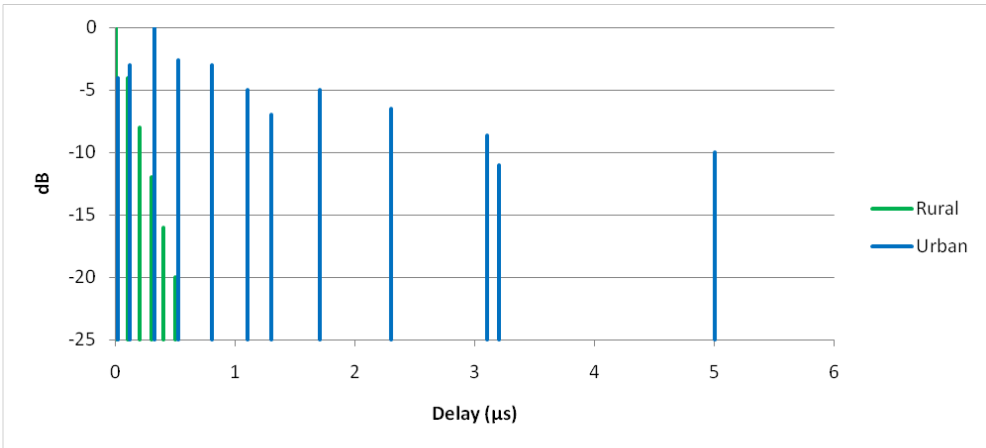

Figure B.2: Channel profiles from COST 207 / EN 50248

The EN 50248 profiles, reproduced above, may be compared with the BBC measurement at UHF. It can be said that the form of the COST 207 urban profile is not contradicted by the BBC results, but this is, of course, only an anecdotal comment. A significant amount of data measured at Band III would be needed to support the use of the COST 207 profiles for DAB coverage planning.