Prediction of the 'useable' coverage of FM radio services

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1 INTRODUCTION

This document reports on the results of a study to examine the relationship between the planning assumptions used to predict FM coverage, and the actual reception conditions experienced by listeners today. Particular attention is given to the characteristics of the receiver population with respect to sensitivity and selectivity.

The work has been undertaken in the context of the potential transition of some analogue services to digital-only provision, and the consequent need to ensure that existing coverage is replicated in an appropriate manner. Although FM coverage contours, within which 'good' reception can be expected, are clearly-defined for regulatory and planning purposes, it may be the case that what is perceived by the public as the 'acceptable' or 'useful' service area may extend much further. It is likely to be the latter limit that defines the public expectation for service replacement by digital radio.

This study has consisted of a literature review to understand the origin of the present coverage limits and a limited programme of receiver testing. The results of these two activities have been used in the derivation of tentative new coverage limits for the 'useful' service area of FM stations.

2 FM RADIO PLANNING STANDARDS

2.1 Current UK planning assumptions

The current planning standards for FM services in the UK can be easily stated:

An area is deemed to be served if:

- The median wanted signal exceeds 54 dBµV/m at a height of 10 m above ground.
- The wanted signal is protected against interference from other FM services for 99% of the time (95% time for local radio)
- The required interference protection ratios are those given in ITU-R BS.412 for stereo services (e.g. 45 dB for co-channel ‘continuous’ and 35 dB for co-channel ‘tropospheric’ interference)
- In determining protection ratios, a directional receive aerial is assumed, with a 12 dB front/back ratio and a pattern following that given in ITU-R BS.599
- Free of severe multipath distortion

It may seem that some of these assumptions completely fail to reflect the way in which FM radio is generally received today (in particular the reference to a directional aerial at a height of 10 m).

In practice, however, most engineers feel that these limits give coverage areas that are pragmatically appropriate. Use of a rooftop antenna will generally give quality good enough for a demanding listener using Hi Fi equipment, and although the signal available from a low height, low gain aerial on a car or portable receiver may be less, the quality of the equipment and environmental noise will tend to mask any degradation of the quality.

As the present study requires that the present limit be reviewed with the aim of recommending a new limit defining the coverage for ‘minimum usable’ quality, it is worthwhile examining the derivation of the present limit.

2.2 Derivation of the present limit

It is unfortunate that the planning standards and assumptions for FM radio are less coherent and less straightforward to relate to network performance than is the case for, say, analogue or digital TV.

The main problem is that the definition of a ‘service’ has changed over the years; in the 1950’s, when the UK network was first established, all receivers were assumed to be fixed domestic sets, using a rooftop aerial at 30 feet above ground. All transmissions were mono - the present stereo system was not developed until the early 1960’s.

In these circumstances, it was straightforward to define a field strength limit that would provide a given audio signal-to-noise ratio at the receiver, and to make appropriate allowance for interference between co- and adjacent channel transmitters, and for external electrical noise

The first major change was the introduction of stereo services in the 1960's and early 70's. Because (i) stereo reception required a higher field strength and (ii) the transmitter network was not reconfigured, it was clear that listeners towards the edge of existing mono coverage areas would not receive a satisfactory stereo service.

At the same time, the problem was being compounded by the rise in listening on portable and car receivers, made possible by the development of low-noise, high-gain transistors. This meant that there were now at least six coverage classes to be considered (i.e. fixed, car and portable, each in stereo or mono).

2.2.1 Original BBC work

The BBC made the first formal trials of FM radio in 1945/6, with low power transmissions in London, Oxford and the Pennines [Kirke, 46]. These trials were made at 45 MHz and 90 MHz It was noted that a '*satisfactory service…can be obtained … at a field strength as low as [34 dBμV/m] from the point of view of receiver noise*".

It was also found, however, that "*the most serious factor in [VHF] broadcasting is … car ignition noise*", and much effort was devoted to investigate this. It was found that ignition noise was worse at 45 MHz than at 90 MHz, and that the use of horizontal polarisation offered some 10 dB of protection over vertical polarisation. The 90 MHz service area was found to show 'higher attenuation and screening effects'.

In [Kirke, 46] two classes of service area are proposed; 'urban' coverage must provide field strengths sufficient to "*provide good service in the presence of considerable motor-car interference*" while 'rural' coverage is limited only by receiver noise. In each area, first and second-class service areas are defined, as shown in Table 1. It is assumed that the receiving aerial is a dipole at 30' above ground level.

Table 1: BBC coverage limit proposals (1946)

Service grade	Description	Field strength (30' agl)
Grade I	1st class urban area coverage sufficient to over-ride practically all motor car interference	66 dBμV/m
Grade II	2nd class urban area coverage sufficient to over-ride practically all motor car interference	54 dBμV/m
Grade III	1st class rural area coverage	46 dBμV/m
Grade IV	2nd class rural area coverage	40 dBμV/m

It is noted that the FCC defines coverage limits of 74, 60 and 34 dBμV/m in large cities, towns and rural areas respectively.

It is interesting that, by 1946, the BBC were proposing that an FM broadcast system in the UK should use vertical polarisation with 75 kHz deviation, 50 μS pre-emphasis and 400 kHz channel spacing for transmitters in the same area, the same parameters used when the service was launched in 1955.

By 1951, following high power comparative trials of AM and FM from the new site at Wrotham [Kirke, 51], the BBC was proposing two classes of service, as shown in Table 2. It is not made clear whether the intention was to ensure that major conurbations received a 'first-class' service.

Table 2: BBC coverage limit proposals (1951)

Service area	Description	Field strength (30' agl)
First class	Impulsive interference from 50% of cars is imperceptible	60 dBμV/m
Second class	The average level of impulsive interference from at least 50% of cars is never graded at worse than 'perceptible'.	48 dBμV/m

In both cases, it is assumed that the "*receiving aerial is within 30-60 ft from a busy road on which the traffic may be continuous*".

Protection ratios are given in [Kirke, 51], of 30 dB (imperceptible) and 25 dB (just perceptible) for co-channel interference and up to 20 dB for adjacent channel (± 200 kHz) interference.

In 1954, FM was formally adopted as the modulation to be used for VHF radio and the BBC service was launched in 1955. The coverage limits [Hayes] were the same as those given in Table 2, with the receiving aerial specified as being "*about 45' from a busy road*". The final co-channel protection ratio adopted was 20 dB (for 99% time), a value which corresponds to 'perceptible' interference[1]. Protection ratios are assumed to fall to 10, 0 and –10 dB at 100, 200 and 300 kHz offsets respectively. These values were based on subjective tests on 'typical' receivers.

In both [Kirke, 51] and [Hayes] it is noted that, because of the high field strengths needed to protect against ignition interference, the system may appear over-engineered in terms of the audio signal/noise ratio achieved for the deviation used (i.e. the required S/N of around 60 dB is obtained for a field strength some 14 dB lower than the 'second-class' contour. The papers point out that (i) the coverage limits refer to median values and that 10% of listeners may obtain a field strength of

[1] On the basis of the ITU propagation curves (Rec.111, precursor of Rec.370) then available, this corresponds to interference being graded 'imperceptible' for 95% time.

40 dBµV/m or less[2] and (ii) many listeners will be using indoor aerials with a reduction in wanted signal of up to 20 dB. These comments are interesting as it is sometimes asserted that neither location variability, nor indoor reception were explicitly catered for in the original planning process.

2.2.2 The coming of stereo

The first (experimental) UK stereo transmissions using the present multiplex system were made from Wrotham in 1962, with a formal service starting in 1966. Expansion was slow, largely due to problems of matched audio distribution to transmitter sites. In theory, multiplex stereo will give a signal/noise level 19.5 dB less than mono, for the same carrier/noise ratio.

It was noted at the time [Philips] however, that the network had been planned with higher levels of field strength than needed on signal/noise grounds, to protect against ignition interference: *"With stereo the position calls for more attention to the aerial arrangement. About 58 dB signal-to-noise ratio (rms.) should be obtainable from […] a 48 dBµV/m field which is the lowest field […] considered adequate for any fm. service in the UK. Ignition interference itself affects stereo only slightly more than mono […]. A yagi aerial would of course be desirable at fringe locations, to counter increased ignition interference as well as reduce background noise.*

In publicity associated with the roll-out of stereo services (1975), BBC Engineering Information Department was advising that *"in general [an aerial] with two or three elements mounted as high as possible outdoors, is required*" Coverage maps of the time indicate two contours of 60 dBµV/m ('good stereo with 2-3 element aerials') and 48 dBµV/m ('larger aerials required').

2.2.3 Local radio

When BBC local radio was introduced [Cummings], [Davis] on an experimental basis in 1967, services were in mono, with the outer coverage defined by the of 48 dBµV/m contour. Interference protection was for 95% time to the appropriate mono protection ratio (28 dB). The primary service area, and the editorial boundaries were, however, defined by the 60 dBµV/m contour for immunity from impulsive interference, good car/portable reception, and the possibility of stereo (with rooftop aerials) at a later date. Some BBC local radio stations used mixed polarisation, giving a 6-8 dB improvement to reception on outdoor portables and cars, though minimal advantage indoors [Spencer, 1970a] [Spencer, 1970b].

Independent Local Radio (ILR) was planned [Sewter] for stereo from the start, but it was assumed that stereo listeners should be prepared to use rooftop antennas with gain. The shortage of VHF frequencies led to protected field strengths as high as 66 dBµV/m (Stereo) or 60 dBµV/m (mono). A virtue was made of this necessity as it was maintained that these high field strengths would be needed anyway for portable

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[2] Implying (simplistically) a location variability of around 6dB

reception with inefficient aerials. All ILR services were introduced using mixed polarisation.

2.2.4 Summary

The original coverage limit of 48 dBμV/m at 10 m applied to mono transmission, and was based on protection against car ignition interference, rather than on ensuring sufficient S/N ratios due to receiver system noise. The value of 48 dBμV/m gives a margin of some 14 dB above the value needed for ‘just perceptible receiver hiss’.

With the coming of stereo, it was necessary to find a further 20 dB of C/N ratio to give the same audio S/N performance at the decoder output. Taking the existing 14 dB and adding a further 6 dB brings the required field strength for ‘just perceptible hiss’ to 54 dBμV/m. However, it should be noted that the 34 dB value is absolute, while the 48 dB is a median figure and allows for location variability (even if this was a post-hoc argument - the original figure having been chosen to allow for ignition interference).

In 1973, BBC coverage maps still indicated contours at 48 and 60 dBμV/m, but by 1980, the only contour given was that for 54 dBμV/m.

2.3 Direct measurements of coverage limits

A BBC study in the 1970’s [Vinnell] compared subjective performance of typical car receivers with known 10 m field strengths for horizontally- and mixed-polarised transmissions. It was found that, for a receiver with an impulsive noise limiter, Grade 3 coverage corresponded roughly to 54 dBμV/m at 10 m. For other receivers a field of around 72 dBμV/m was required.

Surprisingly, no difference in the coverage limit was found between the horizontally-polarised (HP) and mixed-polarised (MP) services, despite both objective and subjective measurements giving better results in the MP case. This was explained because the service area limit had been chosen to represent the point for which 90% of locations were at Grade 3 or above - the median, or other, comparison would have been weighted towards MP.

2.4 ITU-R Recommendations

The 1970 version of BS.412 stated that, in the absence of interference or noise, 34 dBμV/m provides a ‘just acceptable’ service (at 10 m). This is not a median value, but rather the field in which a specific antenna must be immersed.

In the presence of noise/interference, median values of 48, 60 and 70 dBμV/m are recommended for rural areas, urban areas and large cities, respectively. Although these limits are said to be median values, it is not stated what location coverage is achieved, nor what location variability is assumed over what area.

In the current version of the Recommendation, the 34 dBμV/m figure for ‘no-noise or interference’ cases retained for mono reception, but a figure 14 dB higher (48 dBμV/m) is added for the stereo case.

To complement the three mono 'with noise' figures, stereo values have been added that are 6 dB higher in rural and urban areas and 4 dB higher in 'large cities' (i.e. 54 / 66 / 74 dBμV/m).

The rationale for adding a 14 dB allowance for stereo in the 'local field' case and only 4-6 dB in the median field cases is not made explicit, but is presumably because the 34/48 dBμV/m figures define the receiver S/N in the presence of Gaussian thermal noise while the others define protection against impulsive noise.

2.5 EBU Technical note 3236

This EBU paper from 1982 repeats the ITU figures given above, but notes the need for different limit-of-service categories for three classes of receiver, while suggesting that planning for '*near-complete stereo coverage reception on car radios and portable receivers*' is '*unrealistic*'.

Stereo reception should therefore, according to the paper, continue to be planned on the basis of fixed receivers and 10 m aerials, with the further assumption that fringe-area reception will require antennas of 'appreciable gain'. In this case, it is claimed, the 54 dBμV/m limit is appropriate.

No ITU standard exists for car reception, but it is convenient to retain a 10 m reference. Indoor coverage planning depends on assumptions made regarding user willingness to optimise receiver location. Experience suggest a 10 m field strength of 60 dBμV/m (HP) or 54 dBμV/m (VP) is appropriate to provide reception on a portable set with a vertical whip in a downstairs room. Higher values may be appropriate in urban areas.

Similar standards '*… also appear appropriate*' for car reception (assuming well suppressed ignition). It is noted that multipath and fast fading effects result in a poor correlation between reception quality and 10 m field strength.

3 HOW TO DEFINE NEW LIMITS?

While it is important to attempt to understand the origin of the existing coverage limits, what is currently required are justifiable new limits for the 'edge of useful coverage' of FM services.

The primary difference with respect to the normal derivation of service area boundaries will lie in the subjective quality that is to be associated with 'useful' coverage; a 'minimum tolerable' rather than a 'good' standard of reception. This value can only really be obtained from subjective testing of a large number of subjects in different environments, and will be specified as an audio signal-to-noise (S/N) ratio in dB.

The other aspects that will determine where an objective service contour will be drawn are:

- Receiver sensitivity (i.e. the wanted signal level required for a given audio S/N).
- Receive aerial system efficiency (i.e. how efficiently a field strength in dBµV/m is translated into a voltage in dBµV at the receiver input). For a portable set, this will necessarily be measured at the same time as sensitivity, but for car receivers and Hi-Fi tuners a separate value will be required.
- Location variability (how the wanted signal varies across a small area, typically of the order of 100 m across).
- Height loss (the loss in signal between the reference height of 10 m and the typical height of a car or portable receiver aerial.
- Building loss (the additional loss suffered by the signal on entering a building).
- Environmental noise levels.
- Receiver selectivity (the effectiveness with which the receiver rejects interference).

All of these parameters will exhibit a large spread in value. Building loss (wood-framed bungalow vs. stone cottage) and car aerial system performance (roof-mounted quarter-wave whip vs. printed-antenna on window), for example, could easily vary by 10 dB between samples.

A robust approach to the determination of 'useful coverage' limits will need to take explicit account of the statistical variability of these parameters.

3.1 Reception classes

The original coverage limits were, broadly, based on the assumption of a fixed receiver with a rooftop aerial, providing a high-quality service to a listener in a quiet environment.

Given that the vast majority of listening is now to car or portable receivers, it is clear that these should be explicitly considered in defining new limits. Furthermore, as the relevant parameters are different in the two cases (e.g. a separate aerial system is used in a car, while building loss applies in the case of a portable), it would make sense to examine both cases. Finally, it would be useful to retain the fixed receiver case as a reference.

The remainder of this paper therefore considers the following three 'representative reception classes':

Table 3.1: Reception classes

Class	**Hi-Fi**	**Portable**	**Car**
Aerial type	4-element at 10 m	Short whip (~60 cm)	Short whip ('Bee sting')
Mode	Stereo	Mono	Mono
Ambient noise	Quiet	Children, washing machine, etc.	Engine / road noise
Notes	-	Indoor, ground floor	-

Stereo mode is assumed for the 'Hi-Fi' case as it is felt that this would be expected in this role; if FM radio was unable to provide a reasonable stereo service, radio carried by digital TV services (terrestrial, satellite or cable) or internet radio would probably be substituted. Stereo will not, normally be available from portables, however, and may not be greatly missed in a car.

The following section of the report considers each of the parameters listed above, and proposes appropriate values for each of the three reception classes.

4 PLANNING PARAMETER VALUES

4.1 Audio signal-to-noise ratio

This is arguably the most important parameter required to define the 'useful' service area, and the most difficult to specify as it is (i) subjective (ii) will depend on programme content, (iii) on ambient acoustic noise and (iv) on the quality of the loudspeaker and amplifier in the receiver.

4.1.1 Specifying S/N

Discussions of signal-to-noise values are complicated by the large variety of different ways in which this can be specified. Theoretical discussions of noise in FM systems often relate to RMS values of noise with no weighting, and a signal level that relates to the maximum deviation of the system (i.e. 75 kHz).

In a bid to align objective noise measurement with subjective assessment, frequency weighting networks are generally used, so that the measurement is biased more towards noise falling in the most disturbing parts of the spectrum (around 6 kHz) rather than frequencies that are relatively inaudible to the human ear.

Broadcasters in the UK will generally quote S/N levels in terms of noise weighted according to ITU-R Recommendation BS.468 and measured with a quasi-peak reading meter. The signal reference will generally be to zero-level (PPM 4)[3]. This parameter is abbreviated dB4W (BBC terminology) or dBq0p (**q**uasi-peak, **zero**-level, **p**sophometrically-weighted).

Consumer equipment is often seen with S/N quoted as 'A-weighted', rather than BS.468 as this is an alternative US standard (which also, co-incidentally, gives better-looking performance figures for the same equipment). The difference between the two is typically around 10 dB, and will depend on the exact characteristics of the noise spectrum.

From theory and measurement, the following differences are observed:

- Quasi-peak metering gives S/N values some 4 dB less than RMS metering.
- BS.468 weighting gives S/N values some 4 dB less than the unweighted values.
- Reference to PPM 4 (~30 kHz) deviation gives S/N values ~8 dB less than for reference to 75 kHz deviation.

Thus, a textbook figure for S/N in an FM system might appear to be 16 dB better than the same value expressed as 'dB4W'. All S/N values in the remainder of this report are given as 'dB4W'.

[3] See Annex D for a description of these levels and terminology

4.1.2 Subjective S/N requirements

4.1.2.1 BBC

The original BBC work [Hayes] made reference to levels of ‘receiver hiss’, to distinguish thermal noise from impulsive interference. It is stated that a signal-to-noise ratio of 60 dB corresponds to a hiss level that would be graded ‘just perceptible’. It is not stated if this S/N level is weighted, or whether a quasi-peak or RMS value is intended, but it is stated that the ‘signal’ is referred to a deviation of 30 kHz (i.e. to PPM 4).

In another BBC paper from around the same time, reference is made to an ‘ear simulating network’ and RMS measurement, but no specific audio S/N figure is given. The two papers quote measurements giving field strength values for ‘just perceptible hiss’ of 38 dBµV/m and 34 dBµV/m respectively, but if the judgment is subjective, a difference in weighting cannot be responsible for the 4 dB difference.

A substantial exercise in subjective testing was carried out in 1968 [Geddes] with the aim of improving the objective measurement of noise with different characteristics. The main part of this work was concerned with a comparison of weighting networks and meter dynamics, and led to the present ITU-R Recommendation BS.412, but the work started with a series of subjective tests to investigate the subjective impact of different noise levels, in the presence, or absence, of different types of programme. Typical values (for attentive listening in a quiet environment) were between 50-60 dB. One surprising result was that there was only a 2 dB average decrease in sensitivity to noise when programme material was present. No data is available from this work, however, to illuminate a discussion of what would constitute ‘just acceptable’ performance.

4.1.2.2 ITU-R documents

BS.412-9 gives a field strength requirement of 34 dBµV/m for ‘acceptable’ mono service, but does not explicitly relate this to any audio S/N value. The protection ratio values in BS.412-9 (for steady interference) provide 50 dB audio S/N weighted, quasi-peak and referred to 75 kHz deviation. This would equate to **42 dB4W**.

ITU-R procedures for measuring protection ratios commensurate with those in BS.412 are given in BS.641 (“Determination of radio-frequency protection ratios for frequency-modulated sound broadcasting”, 1986, in-force). This Recommendation specifies that, in the absence of interference, the receiver input should be sufficient to give an S/N ratio of at least 56 dB. As this is referenced to 75 kHz deviation, it equates to **48 dB4W**. This value, however, is of no particular relevance, as it is intended simply to ensure that sufficient headroom exists for the protection ratio measurement to be made(in the receiver tests by Nozema, described later, it was noted that most were unable to meet this criterion).

Recommendation BS.415-2 (“Minimum performance specifications for low-cost sound-broadcasting receivers”, 1986, in-force). For FM receivers, the required audio S/N is given as 30 dB, but no information is given regarding weighting, metering or reference, other than to note that "…*The methods of measurement employed should be those recommended in the relevant IEC publications"*.

Recommendation 644-1 ("Audio quality parameters for the performance of a high quality sound-programme transmission chain", 1990, in-force). This document gives S/N values of 51 dB for the entire chain and 56 dB between the transmitter input to receiver output. The measurements of noise level are to be in accordance with BS.412, but it is implied that S/N measurements are to be referred to 'Permitted Maximum Signal' 9 dB above zero level (PPM 4), which would give values of **42 dB4W** and **47 dB4W** for the overall chain and transmitter-receiver part respectively.

BS.704 ("*Characteristics of FM sound broadcasting receivers for planning purposes*", 1990, in-force): Specifies receiver sensitivities with reference to a target audio S/N ratio of 40 dB. This figure is to be measured according to BS.468 (i.e. weighted and Quasi-peak), but is with reference to 75 kHz deviation. The corresponding value is therefore **32 dB4W.** The recommendation implies that receivers should be able to attain ultimate S/N values of **≥ 48 dB4W** for higher input levels. It may be, though it is not explicitly stated, that the lower figure is intended to correspond to the lowest usable sensitivity of the receiver.

4.1.3 Nozema receiver measurements

Ultimate S/N ratio was measured for ten car radios, ten portables and ten 'handhelds'.

The car radios achieved an average of 54 dB, the portables 49 dB and the handhelds 45 dB. These values correspond to **46 dB4W**, **41 dB4W** and **37 dB4W** respectively.

The report notes that most receivers were unable to meet the noise-limited S/N value given in BS.641 (48 dB4W).

4.2 Receiver sensitivities

4.2.1 ITU-R assumptions

ITU-R Recommendation BS.704 ("*Characteristics of FM sound broadcasting receivers for planning purposes*", 1990, in-force): gives sensitivities as follows:

Table 4.1: ITU-R representative receiver sensitivities

Target noise level	Mono		Stereo	
	Ext ant	Portable	Ext ant	Portable
32 dB4W	-95 dBm	30 dBµV/m	-75 dBm	50 dBµV/m
≥ 48 dB4W	-50 dBm	-	-50 dBm	-

NB: S/N is specified in the recommendation as relative to 75 kHz, so the values are 8 dB higher than given here

NB: input powers are specified in the Recommendation in dB(pW). 90 dB has been subtracted to give the equivalent value in dBm.

4.2.2 BBC measurements & assumptions

The original BBC planning was based on the assumption of a mono receiver with a 10 dB noise figure. This would deliver a S/N of 44 dB4W for an input of 35 dBμV EMF.

In the 1990's the BBC undertook a substantial programme of testing of portable receivers. This information is not, however, in the public domain.

4.2.3 Crown Castle receiver measurements

No measurements of receiver sensitivity were made in this study, which related only to selectivity and protection ratio issues. The study itself is not publicly available.

4.2.4 Nozema receiver measurements

This study for the Swiss Federal Office of Communication [Nozema] was primarily concerned with determining protection ratios, and no calibrated measurements of sensitivity were made (coupling signal generators to receivers was by way of crocodile clip on whip antennas.

4.2.5 Threshold effect

For audio S/N below about 25 dB4W, receivers will fall below the 'FM threshold' (see Annex B) at which point the relationship with of audio S/N and input C/N becomes very non-linear, with a small reduction in wanted carrier resulting in a large reduction in audio noise level. The situation is somewhat comparable to the 'digital cliff-edge' transition, though less abrupt. Nevertheless, the S/N can reduce from 30 dB4W (tolerable) to 5 dB4W (unusable) for a reduction in the wanted carrier of only ~10 dB.The effect is seen clearly at around –104 dBm in the measurement below which relates the audio S/N at the output of a Hi-Fi tuner to the level of the wanted carrier.

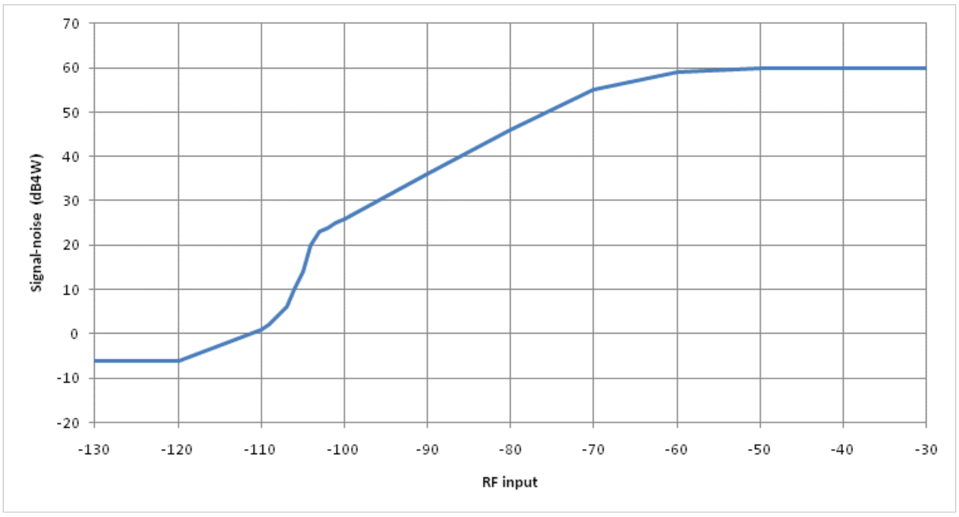

Figure 4.1: Tuner sensitivity measurement (Aegis)

It would, therefore, seem appropriate to set the limit of (mono) coverage at the threshold point, rather than at a specific value of audio S/N. The FM threshold is often defined as the point at which the audio S/N is 1 dB below the value that would be given by extrapolation of the linear trend. This corresponds roughly to the lower limit set in ITU-R BS.704.

4.3 Aerial efficiency

4.3.1 Fixed antennas

The fixed antenna originally assumed to be used by the majority of FM listeners represents a fairly straightforward reference case.

In the original BBC papers, the expectation is that most listeners will install a half-wave dipole at a height of around 30' above ground. By coincidence, the 'effective length' of a dipole at Band II is around 1 m, which implies that, in a field of, say, 1 mV/m, a voltage of 1 mV (EMF) will be available at the feedpoint of the aerial.

Terminating this antenna at the receiver will reduce this voltage to 0.5 mV (PD), and feeder losses will reduce the value further. Typical domestic coaxial cable will have a loss of around 1 dB for 10 m at 100 MHz.

With the introduction of stereo services, it was expected that listeners would be prepared to install multi-element aerials to achieve reasonable S/N levels. A four-element aerial (probably the largest that most listeners would consider installing) will exhibit a gain of around 5 dBd.

4.3.2 Portable antennas

Work [Thoday] by the BBC evaluated the efficiency of a typical short whip antenna, as fitted to the majority of portable receivers. The gain for a whip extended to a length of 260 mm[4] was found to be about –23 dBd. Much of this loss is due to the significant mismatch between the high, and largely capacitative, reactance of the antenna and the receiver input.

This value seems distinctly pessimistic, and is based on a single measurement, but no other measured data has been found in the literature.

4.3.3 Car antennas

Early work by the BBC [Page] proposed a horizontally-polarised V-shaped aerial that exhibited a gain of –13 dBd. This performance was compared with a vertical whip, which offered a gain of around –18 dBd (to HP transmissions).

With the addition of a vertical component to FM transmissions, starting with ILR in the 1970's, the efficiency of car antennas improved significantly. Measurements [Vinnell] on two whip aerials of ~1 m length showed a gain of ~–10 dBd (for mixed-polarisation signals).

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[4] A quarter wavelength is approximately 780 mm in Band II

[1970-35] showed a difference of about 9 dB when the response of car aerials (whip type) to HP and CP[5] transmissions was compared. Absolute values of gain are not given.

4.4 Location variability

Computer predictions of service area typically predict median field strength values for elemental areas (pixels) with des of between 10 m – 500 m. As an aerial is moved around the pixel, the field strength will be found to vary due diffraction and reflection. The standard deviation of this field strength distribution is referred to as 'location variability' It is relevant to note that this parameter has not always been well-defined—it is sometimes taken to apply to a much larger area, or the variation in field strength at a given radius from the transmitter.

In a substantial, and dense, measurement exercise in the 1980's [Taylor] field strengths in Band II were found to have a difference of ~10 dB between the median and 5%/95% points on their cumulative distributions. As the distributions were close approximations to the Lognormal, this implies a location variability of 10/1.645 = 6 dB. Somewhat surprisingly, no significant difference was found between the variability of field strength at heights of 10 m and 1.6 m.

In ITU-R Recommendation P.370-7 (1995, now defunct, but used for the international planning of all FM services in Europe from 1951 onwards), a location variability of 8 dB is specified [P.370]. This figure was derived by reference to measurements over a wider area than that in which it is now generally used, and may represent an overestimate.

4.5 Height loss

It is generally, but not always, the case that, at VHF frequencies and above, higher field strengths will be measured as the height above ground level increases.

This is due to three effects; firstly, there will be fewer obstructions, with smaller incidence angles, between the terminals at greater heights. This will lead to lower diffraction losses. Secondly, and particularly at frequencies less than around 200 MHz, coherent ground reflections may lead to patterns of constructive and destructive interference, giving a non-monotonic variation of field strength with height. Finally, for horizontal polarisation, the boundary conditions of the wave equation require that the electric vector be zero on perfectly-conducting ground. In the real world, this condition ensures that horizontally-polarised waves are severely attenuated at low heights (this was one of the reasons for the adoption of mixed polarisation).

[5] Where the transmitted CP power is 3dB greater than the HP.

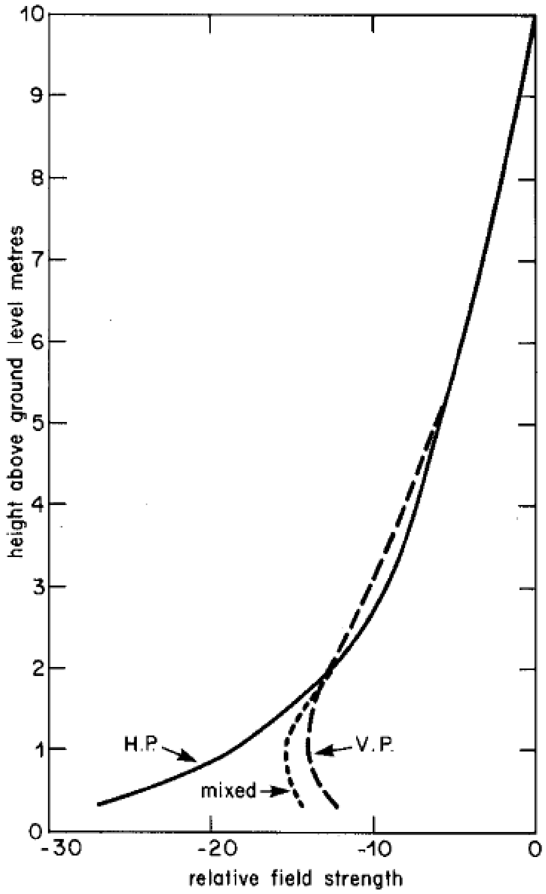

Figure 4.2: Height gain curves [Vinnell]

The BBC [Taylor, 1985] undertook a comprehensive series of measurements, in the Northampton area, of the signals from five transmitters (ranges between 1 km and 70 km. The average height gain between 1.5 m and 10 m was found to be **11 dB** with an SD of ~2.7 dB. No difference was noted between the gain in rural and suburban areas.

Other measurements [Taylor, 1986] in the Wenvoe service area in South Wales [Taylor, 1986] found an average height gain, from 2 m to 10 m, of **10.4 dB** for VP and 12.7 for HP.

[Spencer, 1970b] reported an average height gain of (0.9 m – 10 m) of **14.5 dB** for CP transmissions received on a VP antenna and of 19.3 dB for HP transmissions received on an HP antenna.

[P.370] gives values of **11.0 dB, 14.0 dB** and **16.5 dB f**or the gain between 1.5 m and 10 m in rural, suburban and urban areas respectively.

4.6 Building loss

Little data has been found in the literature regarding building penetration loss at Band II frequencies, with most recent work concentrating on the higher frequencies used in cellular telecommunications systems.

There is no agreement on the way in which such measurements should be made or expressed, although indoor measurements are often referred to outdoor measurements made at the same height. It is suggested that, for FM planning purposes, the most useful statistic would relate indoor fields to the median field at 10 m, as this would avoid the need to combine two statistical distributions (that of height loss from 10 m to, say, 1. 5m and that of the building loss itself).

4.6.1 BBC measurements

Measurements [Thoday] by the BBC in a number of suburban homes found a median building loss of 13.6 dB with reference to the outdoor field at 10 m (of a vertically-polarised transmitter). The standard deviation was 7.5 dB.

Other BBC measurements [Green] have investigated building loss at 211 MHz (for DAB), relating the indoor field to that measured outside at 2 m above ground level. This work found that the median loss to locations on the ground floor was 7.9 dB with a standard deviation of 3 dB.

4.6.2 ITU-R

The Recommendations of the ITU-R offer little guidance in this area at present. Recommendation P.1406-1 ('*Propagation effects relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands*' 2007) simply notes:

"Propagation losses incurred through entering a building can vary considerably depending on the type of building and the construction materials. The frequency of the signal and its angle of incidence are also significant. Consequently, loss values can range from a few to many tens of decibels.

These losses are being investigated in detail by several organizations. It may be that, eventually, a range of building subcategories will be defined, each with its own representative loss statistics".

The definition of Building Entry loss is also unclear: P.1406-1 states:

"*Losses due to penetration into buildings have been defined as the difference between the signal measured outside at street level and that measured inside the building*".

In another Recommendation (P.1411-5), however, the ITU state:

"*Building entry loss is the excess loss due to the presence of a building wall (including windows and other features). It is defined as the difference between the signal levels outside and inside the building at the same height".*

4.7 Environmental noise

ITU-R Recommendation P.372 [P.372] gives information on noise levels from all sources (atmospheric, galactic, man-made) across the radio spectrum. Much of the content on man-made noise has recently been updated on the basis of material derived from an Ofcom research project undertaken by MASS consultants.

This project comprised an examination of the ways in which man-made noise might usefully be quantified, and a measurement campaign that recorded such noise at eight UK locations over a range of frequencies.

The work characterised the measured noise as 'impulsive' or 'white Gaussian', and extracted parameters characterising each type of noise from the measured amplitude probability distributions (APD).

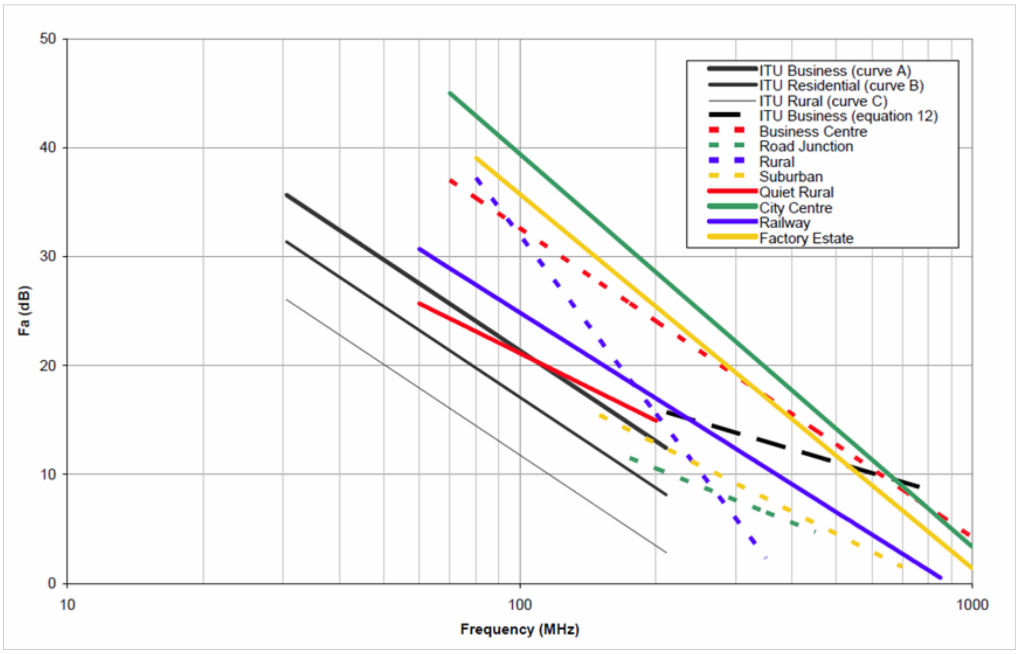

Figure 4.3: External noise figure (Fa) for white Gaussian noise versus Frequency [Wagstaff]

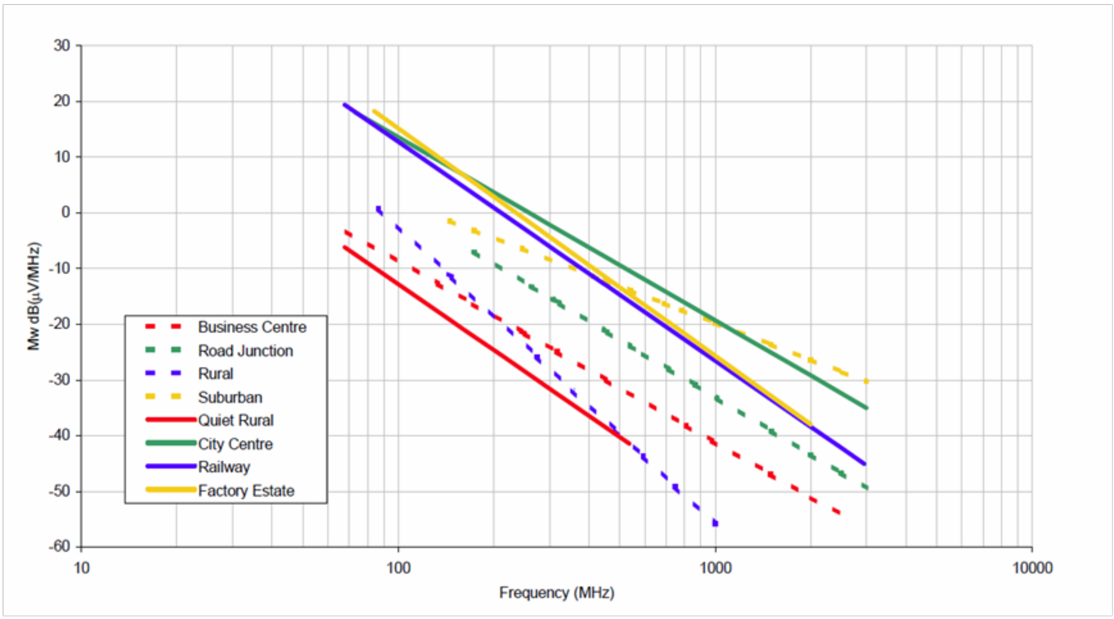

Figure 4.4: Mean impulsive noise voltage density (Mw) versus Frequency [Wagstaff]

It is beyond the scope of the present study to interpret the implications of the measured noise levels in terms of the performance of FM broadcast reception. This would, in particular, require careful analysis of the relationship between the temporal characteristics of impulsive noise and the bandwidths applicable to FM radio.

It can, however, be noted that noise levels show a linear decrease with frequency, and that for both impulsive and Gaussian components, noise is some 10 dB lower at DAB frequencies than in Band II.

4.8 Receiver selectivity

The assumptions made by UK planners regarding receiver selectivity are those given in ITU-R BS.412, which gives curves of necessary protection ratio versus frequency offset. These curves are intended to set a benchmark for high-quality reception, and are reproduced below.

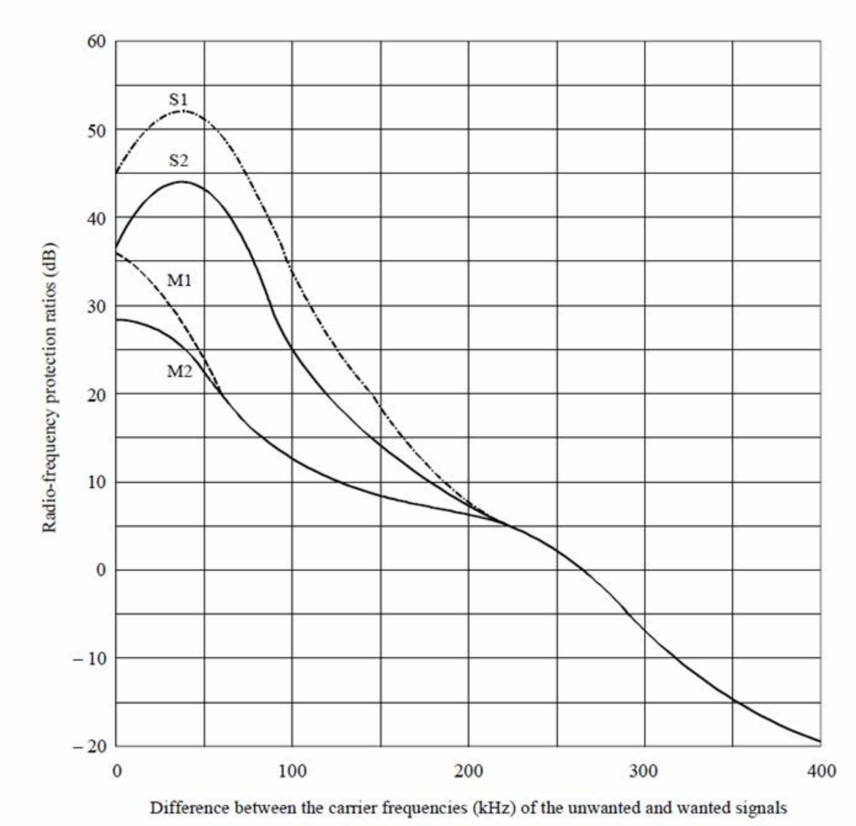

Figure 4.5: Protection ratio curves for FM broadcast reception [from ITU-R BS.412-9)

These curves cover both mono and stereo reception ('M' and 'S') and apply for continuous interference (i.e. from local transmitters) and short-term interference (i.e. from distant transmitters when ducting allows) as indicated by dashed and solid lines respectively.

In the light of increasing congestion of the FM band in many countries, there has been considerable interest in the possibility of relaxing these criteria. This would be made possible either by ensuring the RF and audio synchronisation of multi-frequency networks, or by assuming that most listening is in environments where subtle interference effects are masked by environmental noise (and programme material). This was the starting point for the so-called 'Zerobase' re-planning project in the Netherlands, which achieved a greater degree of frequency re-use in the band, although not without technical and consumer problems.

The context of the present project is different, in that we are not seeking to change any existing allocations, but only to understand at what point interference would render a service 'unusable'. It has already been suggested in Section 3.1, that portable and car reception should be judged on the basis of mono reception, and the corresponding curves of Figure 4.5 will therefore be applicable. Measurements described below explore the degree to which these curves correspond to actual receiver performance.

5 COVERAGE LIMITS

The Information summarised above on parameter values relevant to FM coverage definition is applied in this section to derive tentative values for 'usable' FM coverage limits.

As proposed in Section 3, separate limits are derived for three 'reception classes': 'Hi-Fi', 'car' and 'portable'.

It should be stressed that the primary purpose of the tables in this section is to set out the parameters that are required to be defined in a formal link budget for FM broadcasting, and to highlight where information is missing or unreliable. The values given below for these parameters are intended as tentative suggestions, rather than as firm proposals.

5.1 Hi-Fi tuner

The case of the Hi-Fi tuner is included for completeness. The relatively high quality assumed to be required in this case implies that such reception is unlikely ever to define the outer limit of usable coverage.

Class	Hi-Fi	Notes
Mode	Stereo	
Required S/N (dB4W)	45	
Noise Figure (dB)	7	
Required C (dBm)	-68	Based on calculated mono value +20dB
Height loss (dB)	0	assumed at rooftop height
Feeder loss (dB)	1	10m cable run
Building loss (dB)	0	
Field req'd at dipole @ 10m (dBµV	49	
Aerial gain (dBd)	5	4-element yagi
Min. required FS (dBµV/m)	44	
Location variability	6	8dB assumed in P.370. Reasonable to assume less in our context
Required %-coverage of 'pixel'	70%	Assume aerial can be positioned to maximise signal
Correction for median (dB)	3.1	assuming log-normal variability
Minimum median FS (dBµV/m)	**47.1**	No allowance for interference

5.2 Car

For the case of in-car reception, the required carrier at the receiver has fallen significantly to reflect mono reception, at just above the FM threshold.

Class	Car	Notes
Mode	Mono	
Required S/N (dB4W)	30	Just above threshold
Noise Figure (dB)	10	to reflect ignition noise, etc
Required C (dBm)	-100	calculated mono value
Height loss (dB)	11	From Northampton experiment. Use median value (SD < 3dB)
Feeder loss (dB)	0	
Building loss (dB)	0	
Field req'd at dipole @ 10m (dBµV/m)	26	
Aerial gain (dBd)	-10	BBC RD 1970/35
Min. required FS (dBµV/m)	36	
Location variability	8	as assumed in P.370.
Required %-coverage of 'pixel'	70%	Assume aerial can be positioned to maximise signal
Correction for median (dB)	4.2	assuming log-normal variability
Minimum median FS (dBµV/m)	**40.2**	NB: no allowance for interference

It is assumed that field strength variation is greater at car roof height than at 10 m, although a 70% coverage requirement 'per pixel' has been retained. The appropriate value for this parameter could only be set by extensive consumer research, but seems likely to be somewhat greater than 50%.

Perhaps the greatest uncertainty in this link budget is the performance of car antenna systems. There is little information publicly available on the measured performance of such systems, and this would be a fruitful area for further work.

5.3 Portable

Class	Portable	Notes
Mode	Mono	
Required S/N (dB4W)	30	Just above threshold
Noise Figure (dB)	10	to reflect termostats, domestic equipment
Required C (dBm)	-100	calculated mono value
Height loss (dB)	0	included in building loss
Feeder loss (dB)	0	
Building loss (dB)	13.6	Median value from [Thoday]. Assume co-operation finding 'sweet spot'
Field req'd at dipole @ 10m (dBμ\	28	
Aerial gain (dBd)	-23	[Thoday] value for 260 mm whip
Min. required FS (dBμV/m)	51	
Location variability	8	8dB assumed in P.370. Reasonable to assume less in our context
Required %-coverage of 'pixel'	70%	Assume aerial can be positioned to maximise signal
Correction for median (dB)	4.2	assuming log-normal variability
Minimum median FS (dBμV/m)	**55.2**	NB: no allowance for interference

The portable receiver case includes parameters with significantly more uncertainty than the car case. There is little information available on either receiver aerial system gain, or on building penetration loss, although the former parameter is explored in the measurements described in the next section.

5.4 Commentary

The values given above are tentative, and refinements are discussed below in the light of the receiver measurements. The values were obtained 'blind', and have not been iterated, so it is comforting to note that they probably accord with anecdotal expectation.

In the context of coverage replication, the value obtained for the 'usable' coverage limit for car reception is potentially worrying, as this will probably include large, sparsely-populated rural areas.

6 RECEIVER TESTING

6.1 Sensitivity

Two types of measurements have been carried out to investigate the sensitivity of typical FM broadcast receivers. Conducted measurements have been made on receivers with inputs for external antennas (e.g. Hi-Fi tuners and car radios), while portables or similar radios with telescopic or wire antennas have been measured using reference fields established in an anechoic chamber.

6.1.1 Conducted measurements

The arrangement used for the conducted measurements is shown in Figure 6.1, below. The signal generator was coupled to the receiver under test using an RF transformer (mini-circuits part FT-1.5-1) to give the correct receiver termination. For the car radios, where the only output signals readily available are the loudspeaker connections, a low-Z to high-Z transformer was used to couple the receiver to the test set (a BBC ME2/5).

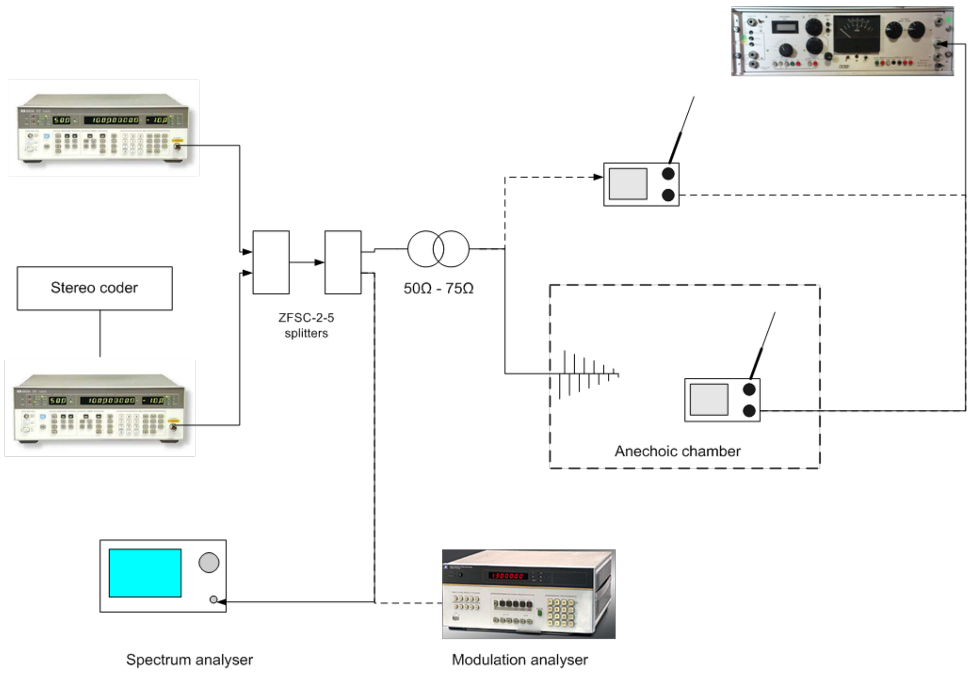

Figure 6.1: Conducted measurement setup

The FM signal generator, modulated by a 400 Hz tone, was set to give a peak deviation of 60.8 kHz, verified using the HP 8901A modulation analyser. This level corresponds to PPM 6, and was used as the reference point for the S/N measurements, with the output of the device under test being adjusted to give a centre-scale reading (un-weighted) on the test set with the test set audio attenuator set to zero.

The modulation was then switched off, and the RF output of the signal generator reduced incrementally[6], noting the increase in (weighted) audio S/N as the receiver input voltage fell.

When plotting the final results, 8 dB was subtracted from the S/N, to give the value of weighted noise expressed relative to zero level (i.e. the 'dB4W' value).

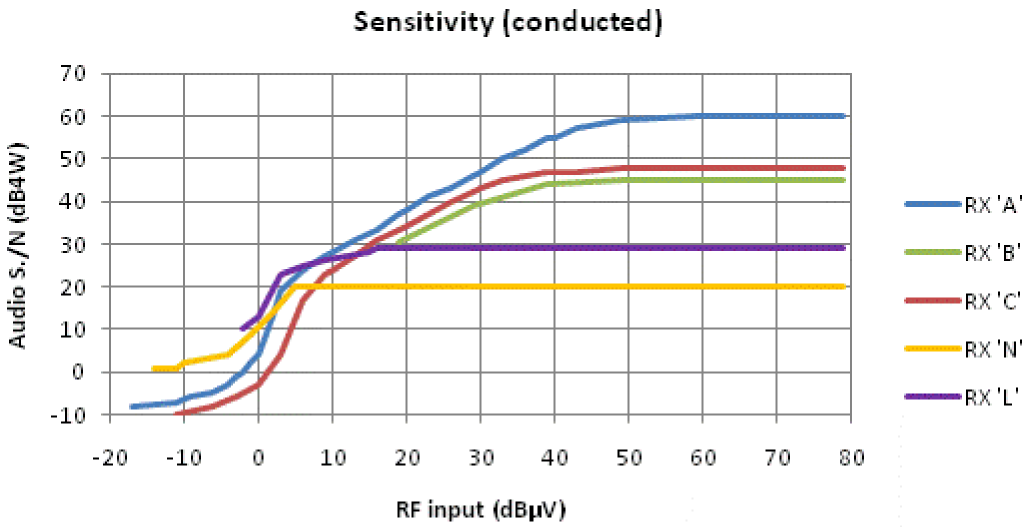

Figure 6.2: Conducted sensitivity measurements

The results for the three high-quality domestic sets (receivers 'A', 'B' and 'C') exhibit a textbook response, with a plateau at the ultimate S/N of the set (limited by the S/N of the AF amplifier stages) followed by a linear relationship between input voltage and S/N until the FM threshold is reached, at which point the S/N degrades sharply. The sensitivity of the three domestic sets is equal to, or exceeds, that assumed in the table of section 5.1.

The car radios tested (receivers 'N' and 'L') show sharply different characteristics, with a rather low ultimate S/N that is invariant until the threshold is reached. In the case of the more modern set (receiver 'L') it appears that some signal processing may be used to modify the IF or AF bandwidth, and to initiate 'soft muting' in response to falling input voltage.

It is also possible that the low values of ultimate S/N measured for the car radio is an artefact of the measurement system and is related to the low setting of the volume control that it was necessary to use.

6.1.2 Radiated measurements

The radiated measurements were conducted in the same way as the conducted tests, but with the signal generator driving a standard dipole in an anechoic

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[6] Having first established that the initial value (typically –30 dBm) gives the ultimate S/N from the receiver.

chamber. This was used to establish a known field strength (at a range of 5 m) in which the receiver under test could be placed.

Audio connections were made to the receiver via a unbalanced-balanced transformer, matching the low-Z receiver output to the high-Z balanced input of the audio test set.

The results from the chamber tests are summarised in Figure 6.3.

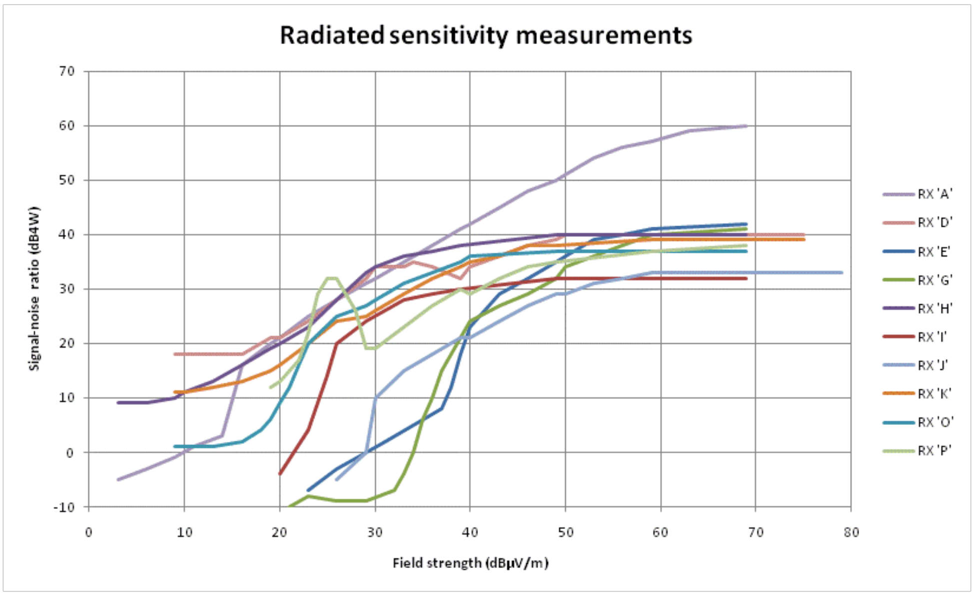

Figure 6.3: Radiated sensitivity tests

A Hi-Fi tuner (Receiver 'A') was included in the tests, connected to a simple (consumer grade) half-wave dipole as a reference. It can be seen that, as might be expected, the ultimate S/N available from the headphone socket of portable radios is some 20–30 dB below that available from the tuner. The use of a half wave dipole also ensures that the best overall sensitivity is achieved.

Of the other sets, the majority reach the FM threshold at a field strength around 20-30 dBμV/m. The two worst-performing sets are both recent contemporary designs including DAB receivers (receivers 'E' and 'G').

The best performing portable sets are three receivers (by the same manufacturer) of 1970's and 1980's vintage.

The anomalous shape of the curve for receiver 'P' is due to the operation of a 'soft muting' circuit which attenuated the audio output for low RF input voltages.

The opportunity was taken to investigate the impact of changes to the length and orientation of telescopic whip antennas on three of the receivers. The results are shown in Figure 6.4.

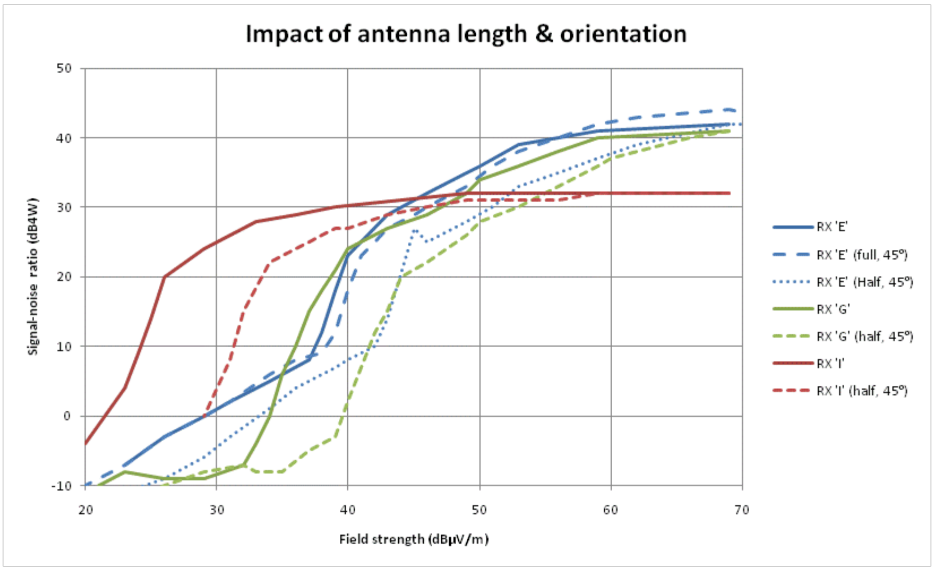

Figure 6.4: Antenna efficiency

It seems that reducing the length of the antenna by 50% typically reduces the sensitivity by some 4–8 dB.

6.1.3 Summary

It seems that the FM threshold, which is a reasonable definition of the limit of 'useful' coverage, is reached at field strengths of around 30 dBμV/m in typical portable receivers.

Assuming a building loss (including height loss) of around 14 dB (see section 4.6), this would imply a coverage limit for indoor portable reception (to 50% locations) of around 44 dBμV/m. This is a somewhat lower figure than the 51 dBμV/m derived in Section 5.3. The difference is largely due to the difference between the BBC value for aerial efficiency, and that measured in the anechoic chamber.

6.2 Selectivity

While testing the receivers, the opportunity was also taken to investigate the selectivity of the samples, and to compare the measured results with the planning assumptions embodied in Recommendation BS.412.

Interference would, ideally, be assessed subjectively by a panel of listeners. Such an approach is beyond the scope of the present project, however, and it was necessary to make objective measurements.

The results of any such measurements will depend on the programme type used for both the interfering and wanted transmissions; louder, more compressed material will tend to generate more interference at wider frequency offsets, but mask low-level interference if used for the wanted signal.

A specification for noise with characteristics appropriate for determining protection ratios is published by the ITU-R in Recommendation BS.559; this could be implemented in software such as MATLAB, and is available as an output from some commercial signal generators, but time and resources did not allow this source to be used.

The interfering signal was, instead, composed of a single tone, modulating a stereo coder to give 67 kHz peak deviation. An RDS subcarrier was also present in the interfering signal. For each offset, the combination of inputs to the stereo coder (i.e. L=R, L, R, or L= –R) and the test tone (1 kHz or 400 kHz) was selected to give the worst interference. The protection ratio was adjusted.

The results from these measurements are shown in Figure 6.5 below, with the BS.412 protection ratios (shown as the bold black line) for reference.

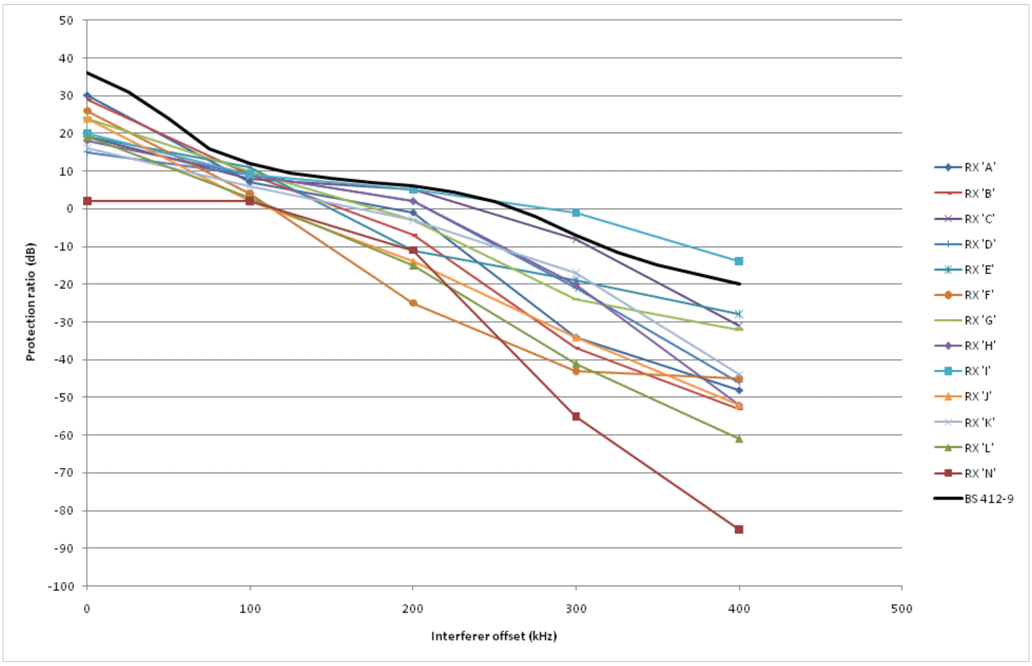

Figure 6.5: Receiver selectivity measurements

It appears that the ITU-R Recommendation represents a reasonable envelope characteristic which will account for the behaviour of all but the outliers in receiver performance.

The spread in performance at ±100 kHz separation is particularly constant between receiver samples, presumably because this will be largely independent of the details of IF filter response. On the other hand, the susceptibility of receivers to interference at ±400 kHz varies dramatically (by some 70 dB); this portion of the response is determined largely by the quality of the receiver front-end, particularly in terms of linearity.

7 CONCLUSIONS

7.1 Link budgets revisited

The tentative field strength limits proposed in section 5 can be reviewed in the light of the measurements described above.

In the case of the 'Hi-Fi tuner' category, the performance of the three domestic receivers measured in the conducted tests agrees well with the sensitivity assumed in the table of Section 5.1.

The car receivers tested also showed a sensitivity that ensured that the FM threshold was reached for an input power (–100 dBm = 7 dBμV/50 Ω) that corresponds to that assumed in Section 5.2. Any revision of the 'usable service area' limit (40.2 dBμV/m) is likely to be a result of a more accurate understanding of the statistics of the gain of representative car aerial systems at these frequencies.

In the case of portable receivers, it seems that the gain of typical whip antennas is significantly greater than was assumed, in Section 5.3, on the basis of the scant evidence available. It may, therefore, be appropriate to revise the figure of 55.2 dBμV/m derived there for the 'useful service area' limit downward by some 10 dB. The author would caution against doing so for several reasons; firstly, the behaviour of portable radio aerial systems is likely to be significantly different in a domestic environment to that measured in an anechoic chamber, as the whip may be in very close proximity to materials that will reduce its efficiency; secondly, the value proposed in Section 5.3 for building loss is, itself uncertain and may need revision; thirdly, levels of radio noise at these frequencies are high in many homes, and this will reduce the effective sensitivity of receivers and finally, anecdotal evidence suggests that a field strength of 55 dBμV/m at 10 m is no guarantee of even 'usable' indoor coverage in some properties.

7.2 Conclusions

The limit of 'usable' coverage of FM radio services is likely to be defined by the distance from the transmitter at which usable mono reception is possible in a car. Both indoor portable reception and high-quality reception with a rooftop aerial are likely to demand higher field strengths.

A figure of around 40 dBμV/m has been derived for the limit of reception in cars, which corresponds well with the 42 dBμV/m currently assumed for planning purposes, given the large uncertainties in many of the parameters.

On the basis of measurements made on representative receivers, it seems that the protection ratio figures for mono reception given in ITU-R Recommendation BS.412 are a valid basis for the determination of 'usable' coverage areas.

7.3 Recommendations

Given the importance of a robust understanding of the limits of FM coverage, and the fact that this is determined by reception in cars, it is suggested that it would be worthwhile to investigate the practical performance of car antenna systems in a representative range of vehicles.

It is further noted that there is very little quantitative data on the statistics of building penetration loss at Band II frequencies; some investigation of this topic would also seem worthwhile.

A ANNEX A: REFERENCES

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B ANNEX B: NOISE IN AN FM SYSTEM

Wideband FM systems can be viewed as the first form of spread spectrum technology, as the bandwidth occupied by the RF signal is deliberately increased (by allowing the modulation index to exceed unity) to obtain an enhanced carrier-noise performance.

The audio signal/noise ratio in an FM system is given as:

$$\frac{S}{N} = 3m^2 \frac{P_c}{2N_0B}$$

Where B is the bandwidth of the modulating signal, P_c the average carrier power, m the modulation index ($m = \frac{\Delta f}{B}$) and N_0 the noise power spectral density (Watts/Hz).

In practical FM systems, a system of pre-emphasis and de-emphasis is used to boost the deviation of higher audio frequencies prior to transmission, and to correct for this at the receiver.

C ANNEX C: SAMPLE RECEIVERS

The following receivers were used in the sensitivity and selectivity tests.

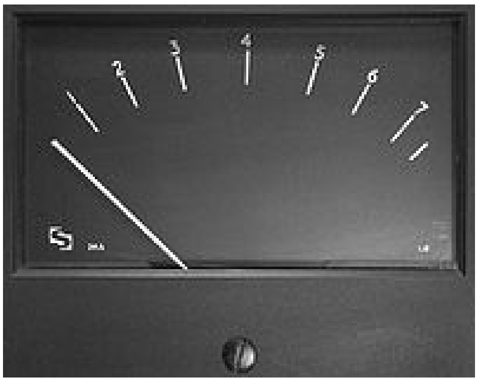
Reference	Receiver type	Notes	Date
A	Hi-Fi tuner	High-specification	2000’s
B	Hi-Fi mini-system	Integrated FM/CD player	2000’s
C	Table radio	Mains powered	2000’s
D	All-band travel portable	PLL tuning	1980’s
E	FM/DAB portable	Small battery portable	2010
F	All-band travel portable	Small, with airband	2010
G	FM/DAB portable	Battery portable	2008
H	All-band travel portable	Analogue tuning	1970’s
I	Large portable	PLL tuning	1990’s
J	Portable CD/radio	Large ‘boombox’	1980’s
K	Portable cassette/radio	Analogue tuning	1980’s
L	Car radio	CD / DAB / FM / MW /LW	2000’s
M	Car radio	Minidisc / FM / MW / LW	2000’s
N	Car radio (old)	FM / MW / LW analogue tuning	1970’s
O	Clock radio	Analogue tuning	1980’s
P	Large portable	PLL tuning, FM / MW / LW	1990’s

D ANNEX D: LEVELS, METERING, ETC

In the analogue broadcast world (in the UK at any rate) audio levels were originally defined with respect to a reference level of 1 mW dissipated in a 600 ohm load (0 dBm).

More recent equipment has high-impedance inputs, and the definition in terms of power has been replaced by an equivalent defined in terms of voltage. As 1 mW will give an RMS voltage of 0.775 V across a 600 ohm termination, the same voltage is now adopted as the standard reference level, but without the expectation that a termination will exist. The level is therefore referred to as *0 dBu* (for *un-terminated*).

In UK broadcast usage, this level corresponds to the midpoint, or '4' on a Peak Programme Meter (PPM) and is generally known as 'zero level' or 'PPM 4'.



Peak Programme Meter

The divisions on a PPM represent intervals of 4 dB, with PPM 6 (i.e. 8 dBu) corresponding to full modulation of the transmitter (100% AM or 75 kHz deviation[7] on FM). Although not a true peak-reading meter, the PPM has a fast attack with a slow decay, and therefore gives a useful subjective indication of programme peaks.

Today the majority of audio recording and transmission is in digital format, and it makes no sense to define levels in terms of voltage or power. A very straightforward alternative is to relate all levels to the maximum value that can be represented by a digital system. If an ADC has 16 bits, the largest number that can be represented is 65,536; if the input exceeds this point, clipping and distortion will occur. This limit is therefore defined as 0 dBFS (for ***F**ull **S**cale*).

It might be thought convenient to associate 0 dBFS with the maximum modulation level of 8 dBu (PPM 6). This would, however, leave no room for transient overshoots too fast to register on a PPM and which would exceed the dynamic

[7] Originally. With the introduction of stereo and RDS, the deviation corresponding to the maximum programme signal has reduced to allow for the additional pilot and subcarrier.

range of the digital system. 0 dBFS has, therefore been defined to be 18 dBu, allowing 10 dB headroom beyond the nominal maximum level.

PPM	**dBu**	**dBFS**	**Note**
1	–12	–30	
2	–8	–26	
3	–4	–22	
4	0	–18	Zero-level
5	4	–14	
6	8	–10	Maximum modulation
7	12	–6	
8	16	–2	
8½	18	0	

Comparison of audio levels

It should be noted that different assumptions apply in the US and other territories where the 'VU meter' is used as an alternative to the PPM.

D.1 Non-broadcast terminology & standards

In some applications, the standard, un-terminated voltage reference is taken as 1.0 V rather than 0.775 V, and this is, logically, specified as 0 dBV.

In professional, semi-professional and consumer audio equipment, references to signal levels can be rather vague, and there is generally no concept of a line-up level. Signal inputs and outputs are often referred to as being at '+4' or '–10', with the former indicating +4 dBu and the latter –10 dBV (–7.8 dBu). The 'line out' socket on a PC is generally at a nominal –10 dBV level.

There seems to be little standardisation of levels in consumer technology—thus, the 'Line out' socket of one particular portable radio is specified as being at –60 dB (0.775 mV) into a 1 kΩ load, while another 'Line out' (on a car radio) is specified as being at 2.0 V into a 10 kΩ impedance. Care is therefore needed in ensuring that measurements are made at the correct operating point of the audio amplifiers concerned.