Spectrum efficiency of wireless microphones

(Final Report)

Ofcom

2202/DWM/R/2/2.0

30th June 2010

Table of Contents

1 EXECUTIVE SUMMARY

This report sets out the results of a series of measurements and trials that were undertaken with the object of understanding the maximum spectrum density at which radio microphones can operate without mutual interference.

Laboratory measurements found that the actual performance of typical professional microphone equipment obtained from hire companies was in close agreement with manufacturers' specifications for sensitivity and adjacent channel selectivity. A more important parameter for determining 'spectrum packing density' is the degree to which transmitters or receivers generate 'intermodulation products' (IPs). This information is seldom quoted by manufacturers, but laboratory measurements found that radio microphone transmitters generate such IPs at significant levels when two or more devices are separated by less than around 1 metre.

If such re-radiated IPs fall on the channel being used by another microphone, interference may be caused, particularly to analogue systems which are more sensitive to interference than the digital systems that are starting to appear on the market. The risk of such interference occurring can often be reduced by simple measures such as ensuring that artists do not leave transmitters active while standing together in the wings.

A series of trials were also conducted to determine the risk of interference between microphones operating at higher-than-usual spectral densities in realistic environments. It was found that up to 15 analogue or digital devices could be used within an 8 MHz TV channel without interference. For the analogue case in particular, the conditions to allow this packing density needed careful control, particularly in respect of the mutual separation between transmitters. Furthermore, it must be emphasised that this density of assignment cannot be extended in a linear fashion (i.e. the use of 30 microphones in 16 MHz is unlikely to be possible)

An examination of existing criteria for the frequency assignment of radiomicrophone systems has found that the complicated statistics of the situation are not adequately accounted for, and a new approach to modelling is proposed.

- Digital microphone systems are typically some 10dB more resistant to interference than analogue systems.
- The most important mechanism limiting spectrum efficiency of microphone systems is the generation and re-radiation of intermodulation products by transmitters separated by less than 1m.
- In carefully-controlled conditions, 15 microphones (digital or analogue) can be accommodated in an 8 MHz channel. This density cannot, however, be maintained for larger numbers of microphones.
- Assignment criteria should take formal account of the statistical nature of interference

2 INTRODUCTION

2.1 Study background

This document is the final report for a study on the spectrum efficiency of UHF wireless microphone systems.

The study, which sought to quantify the relative and absolute spectrum efficiency of digital and analogue wireless microphones, was required in the context of the general background of reduced availability of UHF spectrum for PMSE use, and the specific requirement to ensure adequate spectrum resources for the London Olympics in 2012.

The work within the study, which ran from October 2009 to March 2010, was broken down into six Work Packages, as follows:

WP1: Case study of incidences of high-density radio microphone use

WP2: Desk research on radio microphone performance

WP3: Impact of environment on spectrum efficiency

WP4: Empirical studies of analogue systems

WP5: Empirical studies of digital systems

WP6: Assignment criteria

This document is structured to reflect these work packages, with the exception that the reporting of the empirical studies considered under the headings ‘laboratory’ and ‘field’ trials, rather than being broken down by technology type.

2.2 Radio microphones

Radio microphones are widely used in many parts of the entertainment industry, and by many other commercial, community and amateur groups.

The work reported here has focussed on a specific subset of these applications, specifically the use of UHF radio microphones in professional entertainment applications. This is, in terms of the simultaneous requirement for high spectral occupancy and high quality, the most demanding sector. The use of radio microphones in applications such as business meetings and presentations, church activities or community groups is not covered, nor is the use of VHF radio microphone systems.

Wireless microphone equipment comes in a number of forms; the transmitter may be a separate belt-mounted or pocket module, for use with concealed or semi-concealed microphones or it may be integrated with a handheld microphone for use in applications such as newsgathering, audience responses or use by singers. The receiver may be a rack-mounted unit, perhaps accommodating multiple receivers fed from a distribution amplifier, or it may be a small module mounted on the back of an ENG[1] camera. Some further technical background on microphone systems is given in Annex B.

2.3 Licensing and spectrum issues

Wireless microphones generally use either VHF (175-217MHz) or UHF frequencies, although some devices are becoming available that work at 2.4 GHz . The vast majority of professional use is in the UHF spectrum, generally in the upper part of the television broadcast band, and this study was concerned only with devices operating in this band

In the UK, there are three licensing regimes at UHF:

- Unlicensed use is permitted at 863-865 MHz ("Channel 70‟)
- UK wide use is licensed in Channel 69 (854-862 MHz)
- Frequencies elsewhere in the UHF band (470-854 MHz) can be licensed on a site-specific basis, taking into account the local pattern of use by broadcast transmitters. Channels 67-68 are particularly popular, as they adjoin the UK-wide allocation in Channel 69.

Licensing is currently undertaken by JFMG Limited, acting as an agent for Ofcom. It is intended that this arrangement will be replaced, at a date after the London Olympics, by one in which a "band manager‟ is appointed. The licensing and coordination role will, at least initially, continue to be similar, however.
Much more significant is the impact of spectrum release (the "Digital Dividend‟) following Digital Switch Over (DSO). In a statement published in June 2009[2] Ofcom have indicated that Channels 61-69 in UHF Band V will be cleared of existing users and released to the market, and will no longer be available for use by PMSE. Ofcom have announced that UK wide applications will migrate from Channel 69 to Channel 38, while interleaved, site-specific licences will continue to be available post DSO.

2.4 Interference

There is quite a wide spread in the technical parameters and performance of wireless microphone systems, in particular in terms of the nominal frequency deviation, RF and IF filtering and front-end large signal handling ability. Taken in conjunction with the wide range of deployment scenarios possible, this can make the statistical likelihood of interference very hard to assess.

2.4.1 Interference from other users

The simplest form of interference to manage is that from other users. For UHF wireless microphones, such interference is most likely to be from TV broadcast transmissions. This should be minimised by the assignment criteria used in issuing

[1] Electronic News Gathering

[2] Digital Dividend: clearing the 800 MHz band. Ofcom, 30th June 2009

licences for ‘whitespace’ use, and should not be a problem at all in Channel 69. The relatively high power of TV transmissions can, however, lead to overload problems.

In Channel 69, where some use is not co-ordinated, the possibility also exists for interference from other wireless microphone users.

2.4.2 Adjacent channel interference

The nominal, maximum bandwidth of wireless microphones is 200 kHz, but no filters are perfect, and it is not impossible that some FM transmitters will generate significant energy beyond the notional “Carson’s Rule‟ bandwidth. The JFMG advice is that a safe frequency separation between devices used at the same event is in the order of 350 kHz.

2.4.3 Intermodulation products

The most severe constraint in selecting wireless microphone frequencies is imposed by the need to avoid interference due to intermodulation products (IPs). These arise when mixing occurs between two or more radio signals, generating a spurious signal at a new frequency. The mixing can occur in any non-linear element, which may be a semiconductor junction in the microphone receiver, or corroded metalwork in a building.

In the present context, this is relevant only where the new signals fall within the band used for wireless microphones; therefore, for the two signal (f1 and f2) case, new frequencies might be generated at 2xf1-f2 or 2xf2-f1.

Thus, if two microphones in a theatre are set up to use 856.575 MHz and 858.200 MHz, one of the potential IPs would fall on a frequency of 854.950 MHz, well within the bandwidth of another of the standard channels licensed by JFMG. Interference free operation may well be possible in practice, but there will be a risk that if the receiver (or some other device) receives a strong field from one of the microphones interference might occur to any system using the third frequency.

Several manufacturers provide recommended sets of channels selected to avoid such combinations, or simple software tools that can predict where IPs will fall. The process is non-linear, so the number of IPs grows exponentially with the number of channels used.

2.5 Digital wireless microphones

Digital technology has come late to wireless microphones, partly due to issues of size, cost and battery life but primarily because of the increased latency, or delay, associated with digital signal processing.

The key advantage of digital techniques is the possibility of removing redundancy from signals to allow significant savings in the required transmission bandwidth or storage capacity (e.g. DVB-T television, or mp3 audio devices). Such processing inevitably introduces delays, however, and these are often unacceptable for microphone users. Where the microphone is used in association with digital cameras the delay may be unimportant, as the video channel will also exhibit latency – it is only necessary to harmonise the two to obtain 'lip-sync'. The problem is much more severe for live performance, where both the audience and (particularly) the performer can find delays of even a few milliseconds very disconcerting.

To keep latency to a minimum suggests that the coding should be simple (which implies a greater bandwidth) and that fast processors should be used (implying shorter battery life). The first generation digital equipment currently available features overall system latency of typically 3.6 ms[3], which compares with a recommended maximum of 2ms[4] for professional theatre use, where a critical issue is the audio/performer lip synchronisation. When considering the impact of latency, it should be borne in mind that digital mixing desks are increasingly common, and that these will also add to the overall system delay. Despite the inherent latency, some broadcasters are using such systems successfully (see Section 3.1 below).

One possible advantage of a move to digital techniques, however, is that the levels of interference that can be tolerated are much higher. Where an analogue device might require a carrier to interference (C/I) ratio of ~30dB (with companding), this might only be 20dB for an equivalent digital device. The implication of this is that, while the same level of IPs may be generated in a given scenario, the digital equipment will be more likely to tolerate these levels.

It should be noted that little digital equipment is yet available; while the Trantec SD7000 series is available for hire from several companies, the Sony DWR/DWT system is aimed at electronic news gathering (ENG) and electronic field production (EFP) applications. Sennheiser and Shure, who are generally considered to be the leading manufacturers of high-end professional equipment, do not currently produce digital equipment.

[3] Sony digital wireless microphone system: DWT-B01, DWR-S01D, DWA-01D

[4] ETSI TR 102 546: Technical characteristics for professional wireless microphone systems

3 EXAMPLES OF DENSE WIRELESS MICROPHONE DEPLOYMENT

One aim of the study has been "*to understand the circumstances in which more than 8 wireless microphones have been (or are being) successfully used in previous (or current) events*"..

As a starting point for this work, Ofcom have made available the latest (June 2009) UHF assignment data for PMSE devices, as collated by JFMG Ltd. The data covers both temporary (event) and annual (location). This information has been broken down to show the number of assignments made in each 8 MHz channel at each location, and a summary of some of the statistics is given in Table 3.1.

Table 3.1: Excerpt from JFMG assignment statistics

Venue	duration	No. allocations per 8 MHz channel		
London Studios	2009	37 (ch.60)	24 (Ch.50)	16 (ch.35, 40 & 59)
BBC TV centre	2009	19 (ch.50)	18 (ch 40 & 51)	17 (ch.41)
ITN	2009	19 (ch.68)	11 (ch.63)	10 (ch.67)
BBC Glasgow	2009	18 (ch.64)	12 (ch.42)	8 (ch.56)
BBC BH	2009	16 (ch.35)	10 (ch.67)	8 (ch.63,66,68)
Elstree (BBC)	2009	20 (ch.49)	14 (ch.39)	
Pinewood	2009	38 (ch.21)		
Shepperton	2009	21 (ch.21)		
Silverstone	18 June 09	13 (ch.23, 62, 69)	12 (ch.67)	10 (Cch.59)
Wyvern Theatre, Swindon	2009	48 (ch.69)	45 (ch.68)	32 (ch.67)
National Theatre	2009	22 (ch.69)	12 (ch.21)	9 (ch.64)
BSkyB	2009	20 (ch.21)	7 (ch.46 & 52)	6 (ch.63, 64,67)
Woldgate school	2009	55 (ch.69)		
Glasonbury[2]	June 09	8 (ch.48)	7 (ch.31)	6 (ch.34, 57)

1: A total of 82 frequencies were used at Glastonbury, but these were thinly spread across the band, with a maximum density of 8/channel

While the JFMG data gives an indication of some of the 'hot-spots' for radio microphone use, it does not allow any conclusions to be drawn regarding the actual density of simultaneous microphone use in one area. Where a large number of assignments are made in an individual channel, it is generally the case that these assignments are used in physically-separate areas.

Some specific examples are detailed in the remainder of this section.

3.1 London-based television broadcaster

The project team visited the London studios of a UK TV broadcaster, who, until a little over a year ago, used 10 analogue radio microphones in the production of their main show. These were replaced in 2008 with 14 digital microphones from Trantec.

A total of ten microphones are normally in simultaneous operation, but all 14 have been used on occasion, with no interference whatever. The frequencies assigned (all in TV channel 55) span less than 5.3 MHz. The main studio in which they are used (Studio 5) is 16.5m x 12.8m x 4m.

An examination of the frequency plan chosen, shows that a very large number of the possible intermodulation products fall on channels used in the plan. This results partly from the choice of frequencies that, with only two exceptions, have an equal spacing (of 375 kHz).

The implication of this successful deployment, using frequencies that might be expected to be problematic, is that either no significant IPs are being generated, or that the digital receiver is robust in the presence of co-channel interference from such products.

The overall system at the studio centre makes use of 8 Sennheiser active antennas (two of which are located in the main studio) feeding a distribution amplifier (non-Trantec) which in turn feeds 7 racks each containing two receivers.

3.2 National Theatre

The National Theatre complex includes three performance spaces, the Olivier (seating 1160), the Lyttleton (seats 890) and the Cottersloe (seats 200-400).

The project team visited the theatre on October 21st, at which time a major production, ‘Mother Courage’ by Bertolt Brecht, was taking place. Featuring a large cast and live band, this production makes use of a total of 43 radio microphones, 16 frequencies for in-ear monitors (IEM) and 6 frequencies for ‘reverse radio’ (control or sound effects actuated by radio links from wings to stage). These 65 frequencies were distributed among 9 channels, with a maximum of 8 frequencies in any 8 MHz channel. All this equipment is analogue.

The frequency plan was drawn up with direct guidance from Sennheiser, the suppliers of the majority of the equipment. Some of the channels used do not appear in the JFMG assignment data, as these were licensed specifically for ‘Mother Courage’ subsequent to the production of the JFMG data.

The physical setup of the radio microphones is that racks of diversity receivers are fed from pairs of antennas located in two mutually complementary positions, near to stage-left. There are a total of 5 racks and so 5 pairs of antennas are used, as shown in Figure 3.1. All the antennas are Sennheiser amplified log-periodic types (the LEDs seen in the picture indicating that the amplifiers are powered).

Figure 3.1: Showing microphone receive antennas in wings of Olivier stage

The receiver racks are shown in Figure 3.2. The majority of the receivers are the high-end professional Sennheiser receivers, the EM1046, seen on the left of the picture with 29 units in four rack units, with the red LED displays. Each rack accommodates a maximum eight diversity receivers and has a pair of aerial inputs (‘A’ & ‘B’ for diversity) which are internally amplified and distributed to the individual receiver cards.

Figure 3.2: Showing receiver racks at Olivier

The remaining receivers are three Shure UR4D dual diversity units, providing a total of six receivers in the flight case on the right of the photograph. These receivers are fed from the fifth aerial seen in Fig 3.1.

With a total of 35 receivers, it appears that 8 of the potential 43 wireless microphone frequencies are unused.

3.3 BBC Television Centre

We understand from Sennheiser that they have provided a frequency plan for analogue microphones that allows the use of 16 frequencies in an 8 MHz TV channel within the same studio at Television Centre. This is, they claim, facilitated by the use of the of EM1046 receivers which have selectivity characteristics allowing such dense re-use. This comment would imply that intermodulation products need not always be the limiting factor in high-density deployment. It should be noted, however, that no such frequency plan has been used operationally at Television Centre.

3.4 'Major UK broadcaster'

The project team visited the studios of another UK broadcaster in the course of the study to understand issues concerning radio microphone operations.

3.4.1 Studio use

All current studios are on the ground floor, and few are adjoining (one pair separated only by a partition, another pair by a corridor). Sennheiser and Sony equipment is used. No digital microphones have been trialled or used to date, partly due to concerns regarding latency and the concatenation of coding errors through the chain, and expense. DECT-based talkback equipment has, however, been trialled, but the high latency has caused too many problems to make it usable.

Some studios are electrically screened, but the two largest are not.

The spectral density of microphones never exceeds 8 per 8 MHz channel. Adjacent studios may use, e.g. channels 54 and 56, but then frequencies from channel 55 might additionally be assigned in either studio.

Diversity antennas are used, often rigged at greater than the 1-2 m minimum separation recommended by manufacturers. IEMs do not use diversity[5], but presenters are sometimes unhappy with the quality achieved. In general, artists are seeking increasingly high quality (including stereo, and full acoustic isolation) from IEM systems.

The overall requirement across the site is for around 96 microphones, 64 IEMs and 50 half duplex talkback systems, the latter operating in 12.5 kHz channels.

[5] Some IEMs are available with receive diversity, making use of the earphone lead for the second aerial.

3.4.2 Non-studio use

The broadcaster uses wireless microphone systems both for studio-based production, and for ENG/OB work. However, neither sports nor news OBs generally make use of wireless microphones. Sports venues, in particular, are generally cabled. Where they are used, a maximum of four channels would be needed, more typically two.

At sports events there are also likely to be radio microphones in use by the public address system within the ground.

Much of the operational work and planning is outsourced, e.g. for light entertainment shows ENG/OB use often finds channel 69 too heavily loaded to be useful, so cameras typically tune between channels 67 and 70, and frequencies in channels 67-68 may be pre-booked.

Sports events are generally self-managed by the broadcaster, and it would be expected that cable ‘drop points’ would be available at most venues.

3.4.3 Interference

Some interference issues have been experienced, typically causing ‘birdies’ or opening the squelch on unused channels. The cause is assumed, by the operators, to be the use of multiple channels in adjacent bands.

One of the studio sets is fitted with decorative neon lights, which seem to cause interference - it is believed that the interference is passively re-radiated, rather than actively generated by the lights.

3.5 Athens Olympics (2004)

We have been in contact with Professor Constantinou of the National Technical University of Athens. Professor Constantinou was responsible for putting in place appropriate arrangements for frequency co-ordination of radio microphones for the Athens Olympics in 2004.

In preparation for this work, spectrum monitoring equipment was installed at all Olympic sites. These measurements recorded not only channel occupancy, but allowed a statistical characterisation of the variability of interference power in each 25kHz block of spectrum in the VHF (174-218 MHz) and UHF (470 - 860 MHz) bands. The situation in Athens at the time of the Olympics posed particular constraints as all but two channels were found to be unoccupied. On the other hand, only analogue transmissions were on-air in 2004, and this allowed radio microphones to be allocated frequencies within active (8 MHz) television channels, so long as the vision, chrominance and sound carriers were avoided.

Across the UHF band (470-864 MHz) an average density of 3.2 microphone assignments / MHz was achieved.

The heaviest demand for frequencies was at the Opening ceremony, during which a total of 300 microphones were used simultaneously. Professor Constantinou emphasised that, quite apart from careful frequency planning, it had been crucially important to implement monitoring and enforcement at each site prior to and during events, to intervene where equipment was set up on incorrect frequencies, or where transmitters were used too close together, thus generating re-radiated IPs.

3.6 Summary

While there is clear evidence that more than 8 microphones can be used in an 8 MHz channel, there are conflicting views as to whether this is advisable.. While the use of 14 frequencies certainly seems to be successful at the studios of the London-based TV company, using digital equipment, the National Theatre reported that they were advised by Sennheiser never to use more than eight analogue microphones in 8 MHz. In contrast, Sennheiser themselves report that they have devised a plan for the BBC in which 16 analogue microphones are accommodated in one channel, while the ‘Major broadcaster’ avoids assignments more dense than eight microphones per 8 MHz.

The differences in practice between different operators reflects the fact that the technical requirements and operational constraints are significantly different in these four cases, as are the details of the equipment configuration in terms of aerials, distribution amplifiers and receivers. It also seems to be the case, however, that the evidence regarding the possible ‘packing density’ of microphone systems is based as much on anecdote as on reliable statistical evidence of performance degradation.

4 EQUIPMENT CHARACTERISTICS

The project team have assembled data from information in the public domain, together with input from stakeholders.

It should be noted that attention has been focussed on professional equipment, as these are the items that are of relevance when considering ‘hot spots’ of spectrum use.

It rapidly became clear, in the course of this work, that only a limited amount of technical data regarding equipment is available in the public domain. Most equipment is easily characterised in terms of tuning range and steps, power output and audio frequency response. Receiver sensitivity is also generally provided. Other parameters, such as IF bandwidth, IF frequencies and image channel response and, crucially for this study, third-order intercept point are either unstated, or given only in rare cases.

Furthermore, no manufacturer provides any indication of “… *maximum spectral efficiency…”* as sought in the ITT. It had been expected that many of these gaps would have been filled in the course of the study, as most of the manufacturers contacted expressed a willingness to provide further technical data on their products, explaining that the information is not made generally available as it is 'unlikely to be of general interest'. This has, however, not generally been forthcoming in the time frame required.

The data gathered has been collated as an Excel workbook, with separate worksheets for analogue and digital equipment. Rather than attempt to reproduce the rather extensive Excel tabulation in this document, it has been provided as a separate file: "***DWM database (25 May 2010).xlsx***". Much of the information in this database is, however, of only minor interest, and the key parameters relating to the most popular radio microphone receiver equipment have been reproduced in Tables 4.1 and 4.2 below. Transmitter specifications have been examined, but none have included information on spurious emissions, or levels of re-radiated IPs

Table 4.1: Analogue microphone receivers

	Sennheiser	Sennheiser	Shure	Sony
Model	EM 1046	EM 3532	U4D (S2)	WRR855S
Type	Rackmount	Dual RX	Dual RX	ENG camera mount
Tuning step	5 kHz	5 kHz	5 kHz	125 kHz
Tuning range	24 MHz	24 MHz	24 MHz	24 MHz
Pre-emphasis	50 µs	50 µs	50 µs	50 µs
Nominal / peak deviation	±40 / ±56 kHz	±40 / ±56 kHz	±18 kHz	±5/±40 kHz
Audio S/N	>117 dB(A) ≥ 105 dB CCIR	≥ 120# dB(A) ≥ 106dB CCIR at 1mV input	102dB(A) dynamic range >100dB(A) ultimate quieting at ±18 kHz	≥ 60 dB(A) at 60dBµV RF input
Sensitivity	1.5 µV for SNR of 52dB(A)	< 5µV for SNR of 90dB(A)	-107 dBm for 12 dB SINAD -102 dBm for 30dB SINAD	
Adjacent	≥ 66 dB	≥ 75 dB		60dB at ±250 kHz
Image	>100 dB	≥ 50 dB 65 dB typ	90 dB typ	
Intermodulation*	≥76 dB			
Intermodulation Attenuation*	≥100 dB	>66 dB (0.4, 0.8 MHz)		
Companding	"HiDyn plus"	"HiDyn plus"	Yes	No (?)
Diversity	2 rx, strongest RF signal selected		Maximum Ratio Combining Audio Diversity	Yes

***It is not clear from the data available how these figures are measured**

 # Also quoted as 117 dB(A) on some data sheets

Table 4.2: Digital microphone receivers

Manufacturer	Trantec	Zaxcom
Model	S-D 7802	RX 4900
Tuning range	30 / 60 / 80 MHz	20 or 36 MHz
Tuning step	Preset (5 groups of 16 channels)	100 kHz
Bandwidth	<200 kHz	200 / 125 kHz (US/EU)
Sampling	32 kHz*, 24-bit	48 kHz, 24-bit
Dynamic range	≥105 dB(A)	114 dB
Sensitivity	-90 dBm	-110 dBm
Adjacent	50 dB	500 kHz min (750 kHz recommended)
Image	65 dB	
Modulation	DQPSK	Proprietary
Diversity	Yes	Yes
Latency	"fast DSP reducing latency to extremely low levels"	6 ms (3.6 ms for US & mono modes)

* A value of 48 kHz is quoted elsewhere

5 IMPACT OF ENVIRONMENT

5.1 Introduction

The environment in which wireless microphone systems are deployed will have an impact on the achievable spectrum efficiency through a number of (largely) separate mechanisms.

5.1.1 Size of venue / density of deployment

A particularly important situation for the generation of intermodulation products occurs when two active transmitters are close to each other, and the coupling between them leads to the re-radiation of IPs. There is, clearly, more likelihood of such situations occurring when many microphones are in a confined space. Generally, this will be a reflection of the type of event, rather than the environment as such, but the implication is that a West End theatre will represent more of a challenge than a sports venue.

5.1.2 Degree of screening

The degree of screening available at a location is an important driver of overall spectrum efficiency, although here the impact relates to interference to and from other venues and users of the spectrum. In particular, operation within a building will ease co-existence with TV services, both in terms of interference from TV transmitters to microphone systems, and from microphones to domestic TV receivers. This is clearly shown in the ‘spectrum availability’ maps prepared for Ofcom by Sagentia.

The degree of screening also has an influence on the density of frequency use possible within, for instance, a multi-studio site. It is unlikely[6] that it would ever be possible to re-use a particular frequency within such a site, but a reasonable degree of screening between studios will mitigate any problems from adjacent channel interference or IPs.

5.1.3 Re-radiation of intermodulation products

In moderately high power radio installations at which multiple frequencies are in use, problems are often experienced due to the generation, and re-radiation, of intermodulation products by nearby metalwork. The mechanism is that currents are induced in the metalwork, and non-linear mixing occurs at accidental semiconductor junctions of dissimilar metals.

Given the low power levels associated with microphone systems, it would not be expected that this would be a particularly important mechanism, and no such re-radiation was observed during the field trials described below.

[6] But not impossible, for example, if digital equipment were in use at a large site

5.1.4 Multipath and fading

Any terrestrial radio system will suffer from multipath fading to a greater or lesser extent. In the simplest case, signals will arrive at the receiver both directly, and by way of a wave reflected from the ground. As the relative positions of transmitter and receiver change, so the directed and reflected path lengths will vary, causing a phase-shift between the two received signals. The voltage at the receiving antenna can, therefore, vary between a peak of +6dB with respect to free-space and a trough that can theoretically result in no signal, but in practice may be some 30dB less than the average signal.

In most situations, multiple reflected signals will be present, not only from the floor or ground, but also from walls, vehicles, street furniture and other objects in the environment. The most severe situation arises where a significant number of reflections are present, and where the direct signal is attenuated by local clutter. Such a channel will exhibit Rayleigh fading in which the probability of a given fade depth increases by a decade for every 10dB (thus if 10% of locations experience a 20dB fade, 1% will experience a 30dB fade).

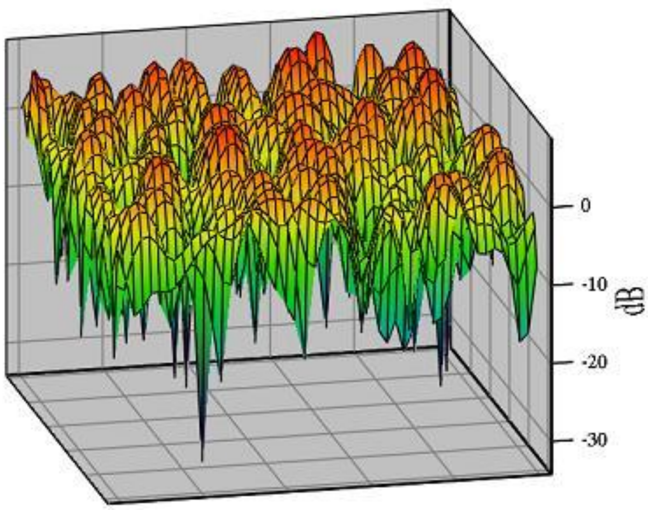

Figure 5.1: Showing Rayleigh fading at UHF over a 3m x 3m area

The overall reflectivity of an environment is, therefore very important in determining the degree of fading to be expected on a given microphone link. Where fading is severe, the system will be more vulnerable to interference from TV services, co-channel microphones of intermodulation products. The degree of reflectivity can be assessed by ‘channel-sounding’ in the time-domain.

5.2 Measured impulse responses

At both the trial locations, channel impulse response measurements were made using the Aegis wideband channel sounder. This device, which operates at 2.4 GHz, uses the autocorrelation properties of a pseudo-random binary sequence (PRBS) to determine the impulse response of a radio channel.

Figure 5.2: Aegis channel sounder (receiver)

In the plots of Figure 5.3, the delay shown on the horizontal axis corresponds to the delay in excess of the line-of-sight path; each delay corresponds to an ellipse of a specific size with the transmitter and receiver of the sounder at the foci.

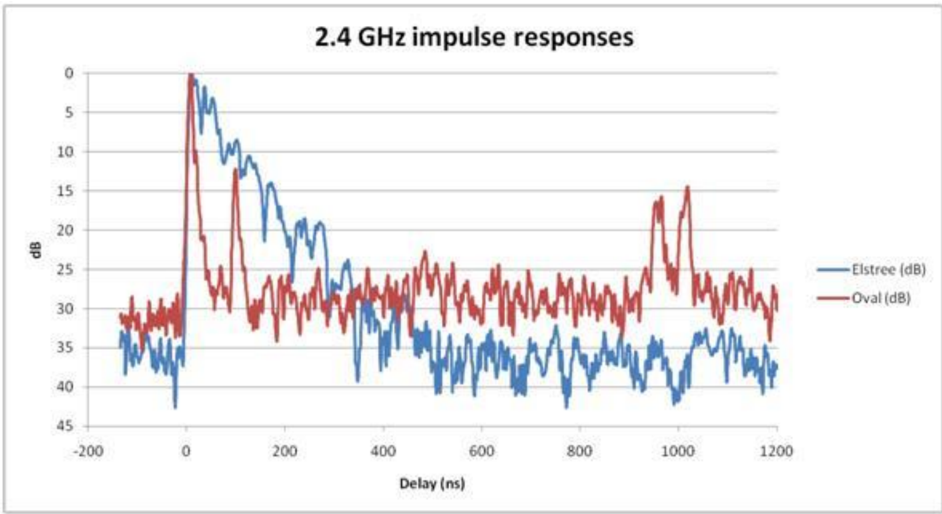

Figure 5.3: Channel impulse responses measured at studio and stadium sites

It can be seen that at the studio the delayed energy falls away smoothly at fairly short delays, showing that the space is generally reflective (i.e. all the delay ellipses' will intersect with some reflective surfaces or objects). The reflections fall into the noise floor of the device at around 500ns, corresponding to a path length difference of 150m.

Figure 5.4: General view of Studio D

The largest dimension of Studio D is 112m, and, for the measurement shown above the transmitter was roughly in the middle of the studio, while the receiver was some 4m from one end wall. The maximum distance (from the transmitter to the far wall and then back to the receiver) is therefore 56 m + 106 m = 162 m. No second order reflections are evident in the plot of Figure 5.3.

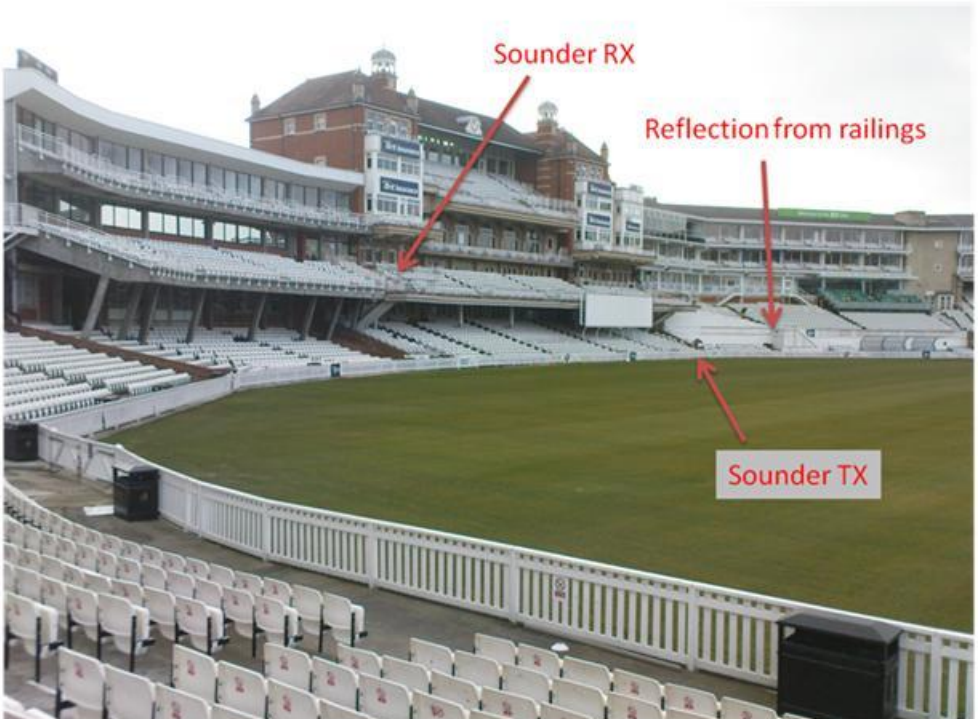

Figure 5.5: Short-delay reflection in stadium

In the 'Oval' plot, the multipath environment is clearly quite different. Firstly, the greater range between transmitter and receiver gives a noise floor that is somewhat higher than that for Elstree. More importantly, although the overall amount of multipath energy is smaller, it is concentrated in a few discrete reflections. The first reflection appears to come from part of the railings on a stairwell behind the transmitter location, while the two longer, more diffuse, delays are from the steel canopy above the North Stand.

Figure 5.6: Canopy generating long-delay reflections in stadium

Such long-delay multipath will give rise to rapid fading in space or frequency domains, and will maximise the audible distortion in FM systems[7], creating a challenge for the radio system designer.

5.3 Conclusions

For the radio planner, the key characteristics of the environment will be:

- The spatial separation available between transmitters, and hence the likelihood of the generation of re-radiated intermodulation products
- The reflectivity and clutter of the environment, which will determine the severity of wanted-path fading
- The shielding available to give isolation to, and from, other radio system

In general, outdoor venues are likely to represent the best case in terms of the first two, while indoor venues will offer better shielding.

[7] No data has been found concerning the ability of digital microphone systems to cope with long-delay multipath. It would be very useful to determine the susceptibility of such equipment to this situation.

6 LABORATORY MEASUREMENTS

6.1 Initial laboratory investigation

In preparation for the main measurement programme, some initial exploratory work was undertaken in the laboratory.

It is generally suggested that the deployment of large numbers of wireless microphones is primarily limited by intermodulation products (IMP or IP), rather than by adjacent channel or blocking effects. IPs arise when mixing occurs between two or more radio signals, generating a spurious signal at a new frequency. In the present context, this is relevant only where the new signals fall within the band used for wireless microphones; Thus, for the two signal (f_1 and f_2) case, new frequencies might be generated at $2f_1 - f_2$ *or* $2f_2 - f_1$.

The mixing can occur in any non-linear element in the vicinity of the radio system. Examples might include:

- An overloaded RF amplifier in a receiver or active antenna
- Corroded metalwork in a building
- A transmitter, in which energy from other transmitters is received by the aerial and coupled to the power amplifier. Non-linear action in the amplifier results in mixing products which are then re-radiated efficiently by the transmitter aerial.

The main aim of the initial investigation was to explore the relative importance of these mechanisms, and to understand practical measurement constraints.

Several stakeholders had suggested that the most important mechanism for IP generation was that of re-radiation from transmitters. The first trials therefore radiated a pair of CW carriers from signal generators into an anechoic chamber, with the intention that the frequencies on which IPs would be expected would be monitored as a variety of devices were introduced to the chamber.

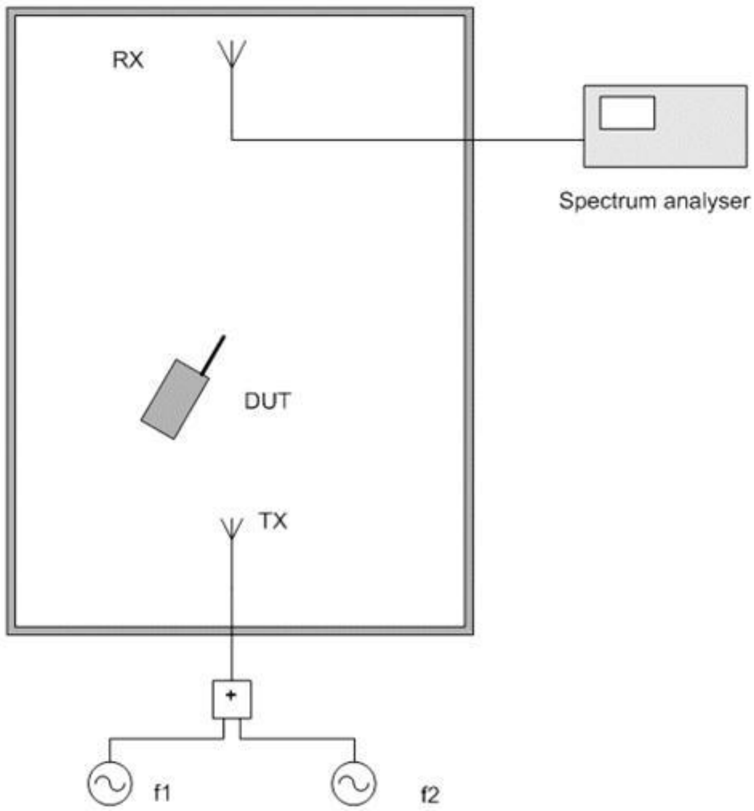

Figure 6.1: Initial test configuration

In the initial configuration, the two carriers were combined and radiated from a single test antenna (a log-periodic 'spade' type), with a second, identical antenna used to feed the spectrum analyser used for monitoring. With the chamber empty, the results shown in Figure 6.2 were obtained for carrier frequencies of 746 and 747 MHz.

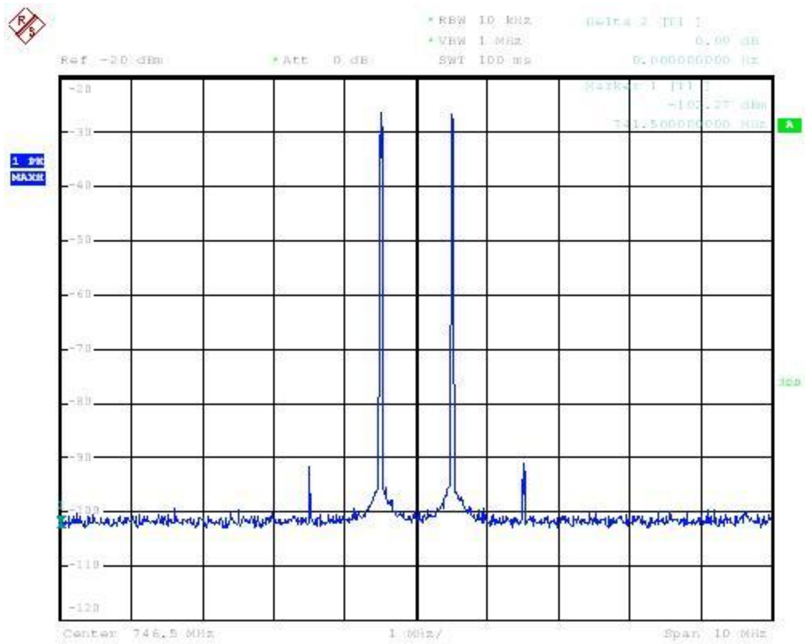

Figure 6.2: Empty chamber showing residual IPs

The third-order IPs on $2f_1$-f_2 and $2f_2$-f_1 can clearly be seen at some 64 dB below the carriers.

A Trantec digital transmitter, operating at 711 MHz was then introduced to the chamber. The device was initially switched off, and the spectrum of Figure 6.3 recorded.

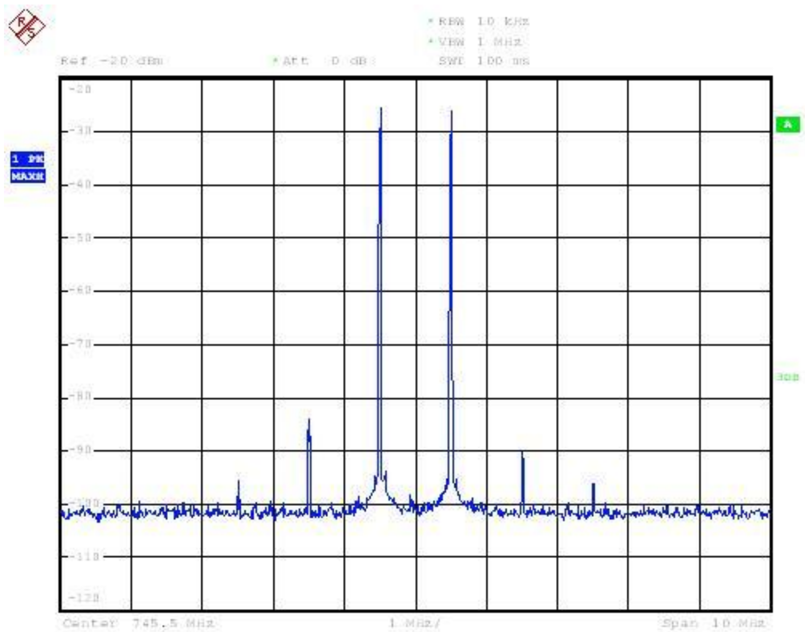

Figure 6.3: With Trantec SD7000 (switched off)

It can be seen that IP levels have increased, with the lower product now only 60dB below the carrier, and with further products (at 744 and 749 MHz) now clearly visible above the noise.

The Trantec transmitter was then switched on (Figure 6.4) and the IP levels were seen to fall back to those of the empty chamber.

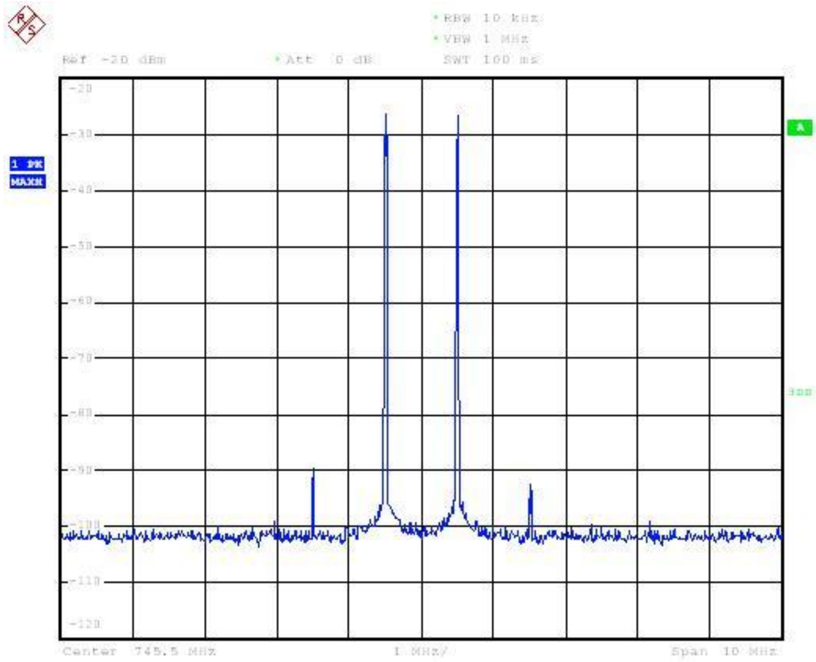

Figure 6.4: With Trantec SD7000 (switched on)

The same measurements were also made with test carriers at 601 / 602 MHz and at 705 / 706 MHz. In both cases an increase in IP levels was only seen with the transmitter switched off. The results at the two higher-frequency pairs were comparable, but at 601/602 MHz the IP levels were almost unchanged (<1dB).

A Sennheiser SK5212 bodypack transmitter (latest-generation professional FM equipment), set to 638 MHz was then introduced to the chamber, with the test frequencies set to 645 / 646 MHz, so as to lie close to the operating frequency of the device (NB: with the chamber empty, the level of the higher IP was found to be significantly higher for these frequencies), The results are shown in Figure 6.5 below.

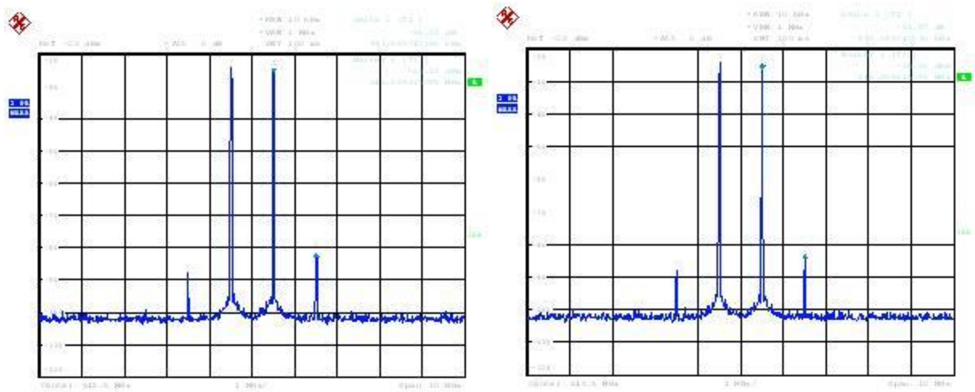

Figure 6.5: With Sennheiser switched off (left) and on (right)

The IP levels with the transmitter off are only marginally (~0.8dB) worse that with the transmitter on. The measurements were repeated at 746 / 747 MHz as shown in Figure 6.6:

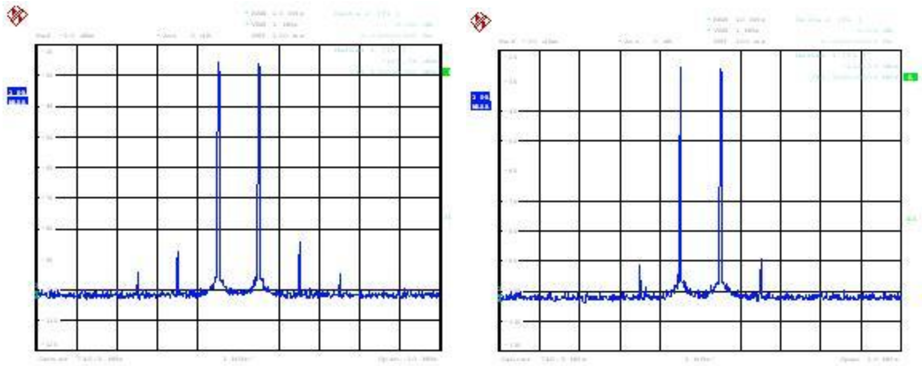

Figure 6.6: With Sennheiser switched off (left) and on (right) at f_{tx} + 100 MHz

In this case, with the incident test signals 100 MHz above the microphone transmitter frequency, the IP levels in the 'microphone off' case were found to increase by up to 6dB with respect to either the 'empty chamber' or 'microphone on' cases. In the worst-case, levels are ~58dB below the wanted carrier.

6.2 'Empty chamber' IP levels

As the IPs that are being generated in the empty chamber (about 59dB below the test carriers in the worst case) are comparable in level with those measured from the devices under test, some effort was devoted to investigating the source of the latter.

Firstly, the Wiltron combiner used to feed the single transmit aerial was investigated by connecting the combiner output directly to the analyser input. The IP levels were found to be around 77dB down, compared with 65dB down via the aerials and the chamber. This component was therefore not the limiting factor.

Next, instead of using a combiner and a single aerial, the two test carriers were radiated from independent aerials, separated by 1 metre. This caused the IP levels to fall by ~7 dB. When a large sheet of metal was placed between the transmit aerials the IPs were found to fall below the analyser noise floor (i.e. at least 74dB below the carriers). It appears, therefore, that the IPs seen in the empty chamber are being generated by non-linear mixing occurring in the test antennas themselves.

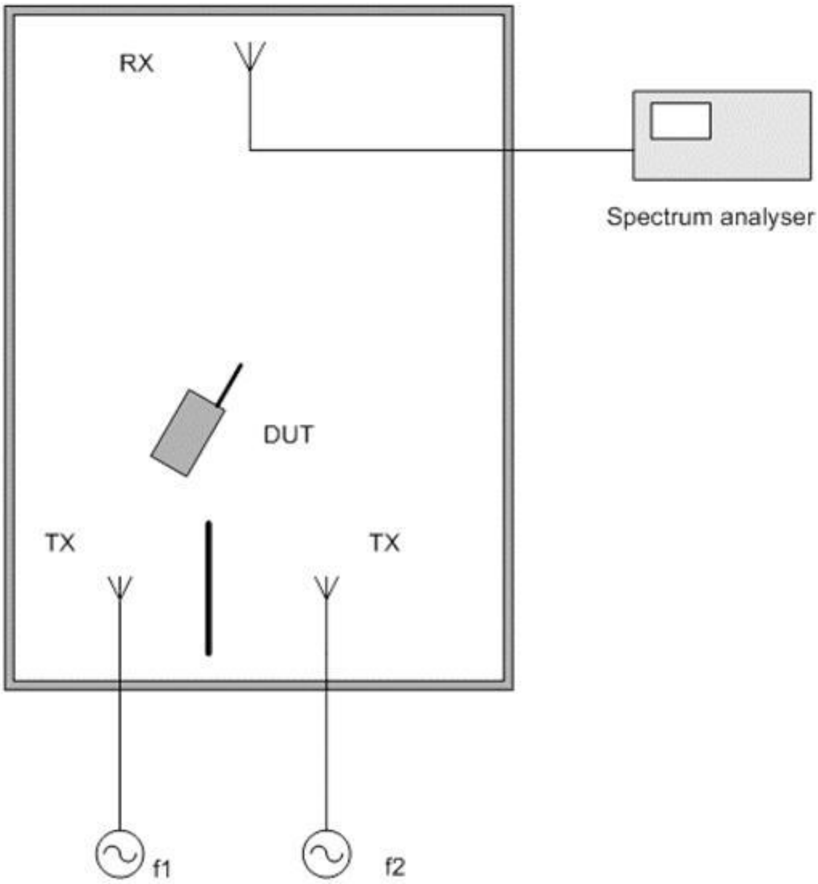

Figure 6.7: Test arrangement with two transmit aerials

The original aim of using signal generators and professional test antennas, within an anechoic chamber, had been to eliminate such spurious signals and to isolate the impact of re-radiation from the microphones. As the test method was introducing IPs comparable with those from the devices under test, a more direct measurement method was then adopted, using the two microphones themselves as the test signals.

6.3 Tests with two radiating microphones

The two microphones available were set to frequencies as close to each other as allowed by their limited tuning ranges; 674 MHz for the Sennheiser and 692 MHz for the Trantec. These frequencies would be predicted to generate third-order IPs at 656 and 710 MHz.

As some interference was experienced from high-power TV transmissions at some of the frequencies of interest, all the equipment was moved inside a screened room. Given the reflective nature of this environment, this also has the advantage of simulating a worst-case, multipath-rich environment, as might be experienced in a studio or theatre with lighting gantries, etc.

In these brief tests, the two microphones were carried by two people moving randomly within the room. IP levels were only found to be significant when the two devices were very close to each other (<30cm). A typical spectrum for such a situation is shown in Figure 6.8.

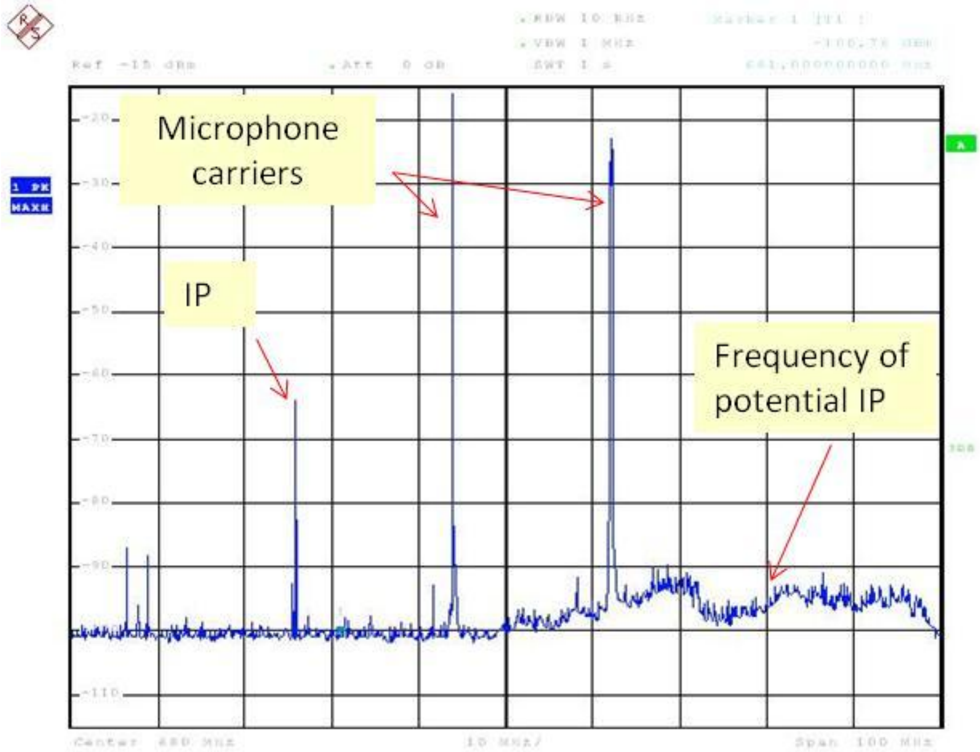

Figure 6.8: Two microphones in close proximity

In this case the lower IP at 656 MHz is very much stronger than that at 710 MHz, at only 48dB below the wanted carrier. The product at 710 MHz is obscured by the high level of noise radiated from the Trantec digital microphone. Figure 6.9 records an attempt to capture the form this spurious radiation more clearly by positioning the antennas to avoid multipath nulls in the spectrum.

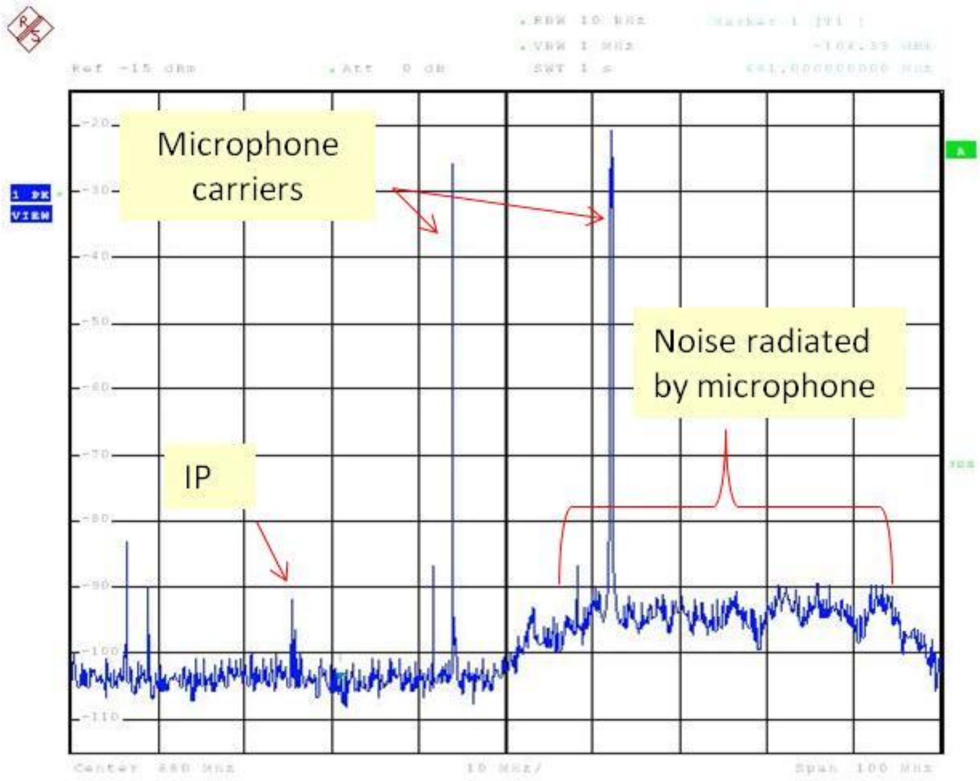

Figure 6.9: Showing spurious noise from Trantec microphone

The radiation has the form of a 45 MHz band of noise, largely on the HF side of the carrier[8]. This noise was not investigated in great detail, but could clearly impose a constraint on system sensitivity in some circumstances (e.g. when such a microphone is close to a receiver antenna which is being used to receive a more distant device transmitting within the noise bandwidth).

6.4 Summary of initial tests

The absorption and re-radiation of energy by radio microphone transmitters does give rise to intermodulation products, as expected. For the two devices tested, however, the levels of IPs are relatively low in most practical circumstances. Furthermore, it seems that significant IPs are not generated when the equipment is switched on. The implications of these re-radiated intermodulation products for overall system spectum efficiency are discussed below.

An initial hypothesis for this behaviour is that the power amplifier transistor in the device is biased into a more linear state (as seen from the aerial port) when the device is powered.

[8] the noise bandwidth correspond approximately to the tuning range of the device, from 692-722 MHz, and therefore probably reflects the characteristics of the output filter.

The two devices exhibited contradictory behaviour in that one (the Trantec digital microphone) generated the highest levels of IP for incident frequencies within, or close to, its own tuning range, while the other (the Sennheiser analogue device) generated higher levels of products when the incident frequencies were 100 MHz above the microphone tuning range.

The digital microphone was found to generate relatively high levels of noise, at ~70dB below the carrier. This behaviour has not been checked against any published specification.

6.5 Receiver sensitivity measurements

Receiver sensitivity is a measure of the receiver's ability to detect a weak RF signal at the desired carrier frequency. There appears to be no consensus between PMSE manufacturers on the test method to use since Signal-to-Noise (S/N) performance in a receiver can be measured or rated several ways. The most common methods are SINAD and S/N ratio.

SINAD is a measurement that approximates the audible background noise heard along with a continuous signal at weak RF levels. It can be measured by running the system at full deviation with a weak RF signal and measuring the level at the receiver output, which consists of signal + noise + distortion. The audio signal is then removed and a second measurement is made to determine the noise + distortion. The results are then expressed as a ratio:

$$SINAD = \frac{Signal + Noise + Distortion}{Noise + Distortion}$$

S/N ratio is a measurement that approximates the background noise heard during pauses in speech when the system is operating at a given RF level. It is normally defined as the amount of RF signal required to produce a certain S/N figure, typically 50 dB. The 50 dB S/N ratio is representative of a minimum useable sensitivity and corresponds to what a non-critical listener would accept. S/N is determined by measuring the system at a given RF signal level at full modulation, with maximum receiver output, then turning off the audio modulation and measuring the remaining noise. This will produce the RF signal level required for a given signal-to-noise ratio.

Both SINAD and S/N measurements are made with an "A" weighted filter to approximate the ear's response to noise.

The following examples show how sensitivity performance is specified by different manufacturers for analogue receivers:

0.34µV input for 12 dB SINAD

0.45µV input for 20 dB SINAD

0.30µV input for 12 dB quieting

0.27µV input for 12 dB S/N

0.47μV input for 30 dB S/N

1.20μV input for 50 dB S/N

For digital receivers, sensitivity tends to be specified in terms of dBm at the input.

The test set-up used for the receiver sensitivity measurements, based on Draft ETSI TR 102 546[9], is shown in Figure 6.10.

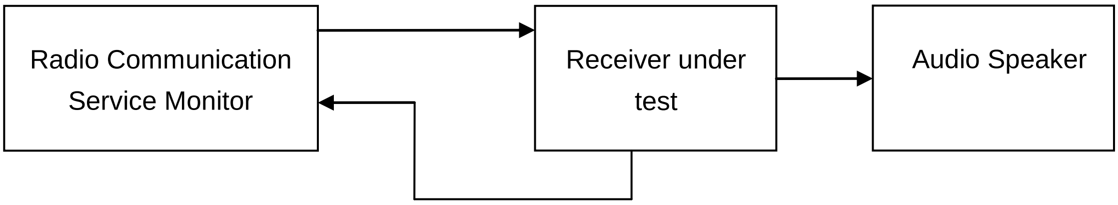

Figure 6.10: Receiver sensitivity test set-up

The following test method was used for analogue receivers:

1. The squelch or gain/volume control was set to a mid range value to represent typical operational conditions of a receiver.
2. An RF level of -120dBm was set on the radio communication service monitor.
3. A modulated 1 kHz audio tone with a frequency deviation of +/- 24 kHz was set on the radio communication service monitor.
4. The wanted RF level was increased until approximately 50 dB S/N ratio was achieved on the receiver S/N display of the radio communication service monitor. The 1 kHz audio tone was also audible on the speaker at this time.
5. The RF level (dBm) at which the 50 dB S/N ratio was achieved was recorded as the receivers' minimum sensitivity value.

Receiver sensitivity measurements were made on 5 types of receiver. The results are presented below in Table 6.1.

[9] Draft ETSI TR 102 546 v1.1.1_2.0.2 (2007-01): Technical characteristics for Professional Wireless Microphone Systems (PWMS); System Reference Document

Table 6.1: Receiver sensitivity measurements

Receiver	Model	Type	Measured Sensitivity (dBm)	Achieved S/N dB(A)
1	AKG SR450	Mid Range Analogue	-93	52
2	Sennheiser EM1046	Professional Analogue	-84	52
3	Shure U4D	Professional Analogue	-95.5	52
4	Trantec SD7802	Professional Digital	-97.1	-
5	Zaxcom RX4900	Professional Digital	-100.18	-

It should be noted that the receiver squelch or gain level setting will have an impact on the minimum sensitivity; the lower the squelch setting the more sensitive the receiver.

For Analogue receiver 2, the tests were repeated for the squelch level set to 0. The corresponding minimum sensitivity was measured as -103.5 dB for S/N of 52 dB, which compares closely with the manufacturer's stated figure.

All receivers measured were found to have a sensitivity that agreed well with the manufacturers' specification. Sensitivity is only relevant to spectrum efficiency in that receivers that are highly sensitive offer the possibility of working at longer ranges, where the microphone system will be more vulnerable to all modes of interference.

6.6 Receiver C/I and Selectivity Measurements

Receiver selectivity is defined as a measure of the capability of the receiver to operate satisfactorily in the presence of an unwanted signal close to the desired carrier frequency. Similarly, blocking is a measure of the receiver to receive a wanted modulated signal without exceeding a given degradation due to the presence of an unwanted signal at any frequencies other than those of the spurious responses or adjacent channels. The test set-up, based on Draft ETSI TR 102 546, is shown below in Figure 6.11

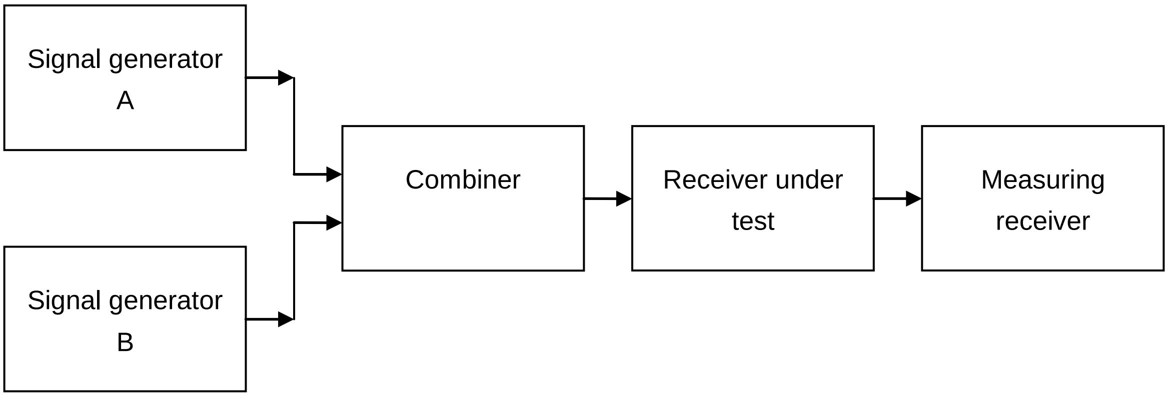

Figure 6.11: Receiver selectivity / blocking test set-up

The following test method was used to determine receiver selectivity / blocking performance:

1. Signal generator A was set to the frequency of the receiver under test (fc).
2. The RF output level of signal generator A was set to a value 20 dB above the receiver's minimum sensitivity, measured at the antenna inputs of the receiver under test.
3. Signal generator A was set to have a 1 kHz audio tone with FM modulation and a deviation of +/- 24 kHz.
4. Signal generator B was set to have an un-modulated CW RF output signal.
5. Signal generator B RF output level was initially set to -120 dBm at the same frequency as signal generator A.
6. The RF power level of signal generator B was adjusted until a 6 dB increase in the noise level was achieved.
7. The wanted signal and unwanted signal levels were recorded using a spectrum analyser in a 200 kHz resolution bandwidth.
8. The C/I protection ratio was calculated from steps 2 and 6.

The above procedure was repeated for frequency offsets up to +/- 8 MHz from the wanted frequency (fc).

The figure below shows that a co-channel C/I protection ratio of 18 to 25 dB is required for the analogue receivers compared with a value of 14dB for the digital receivers.

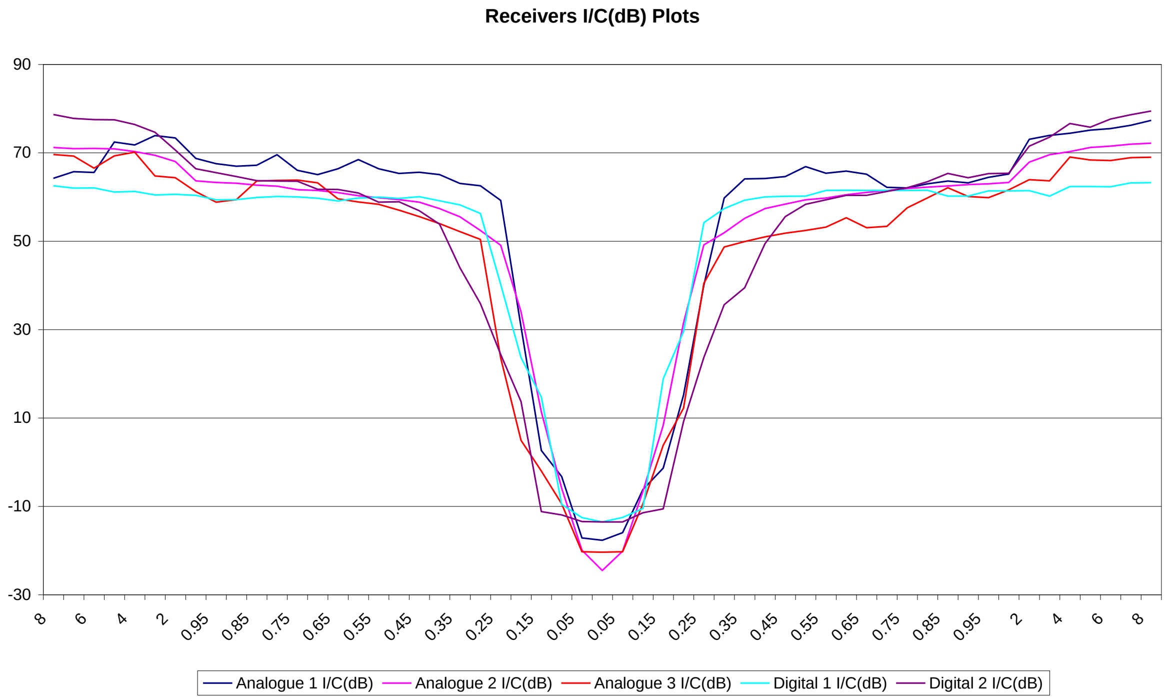

Figure 6.12: Measurement plot of I/C protection ratio for the PMSE receivers

The C/I requirement of a radio microphone system is of key importance in determining the spectrum packing density that can be achieved. As the digital systems have a C/I requirement that is typically 6dB less than that for analogue systems, this implies that re-use distances will be halved (assuming free-space propagation).

Although adjacent channel interference is generally a less serious constraint than that from intermodulation products, the selectivity characteristic of receivers is important. Those measured in the course of the study correspond to the manufacturers' specification, and are representative of the performance that would be expected from high-quality equipment. The performance is adequate to allow adjacent channel operation in neighbouring, but non-overlapping, areas.

6.7 Receiver intermodulation measurements

The test set-up used to measure receiver intermodulation performance, based on Draft ETSI TR 102 546, is shown in figure 6.13 below.

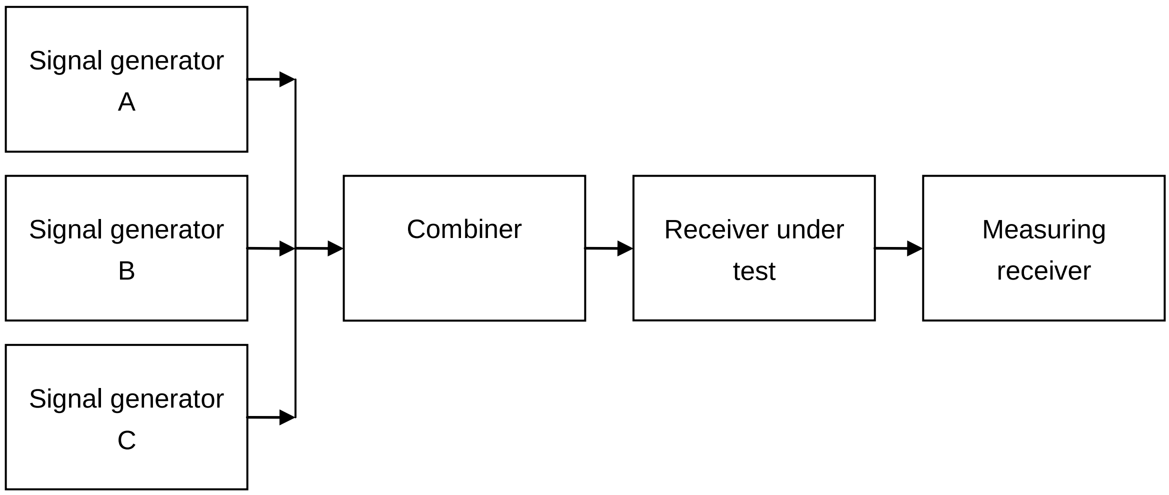

Figure 6.13: Intermodulation/Interferer level test set-up

The following test method was used to determine the intermodulation rejection of the PMSE receivers:

1. Signal generator A was set to the frequency of the receiver under test (fc).
2. The RF output level of signal generator A was set to -80 dBm, measured at the input of the receiver under test.
3. Signal generator A was set to have a 1 kHz audio tone with FM modulation and a deviation of +/- 24 kHz.
4. Signal generator B was set to have an un-modulated CW RF output signal.
5. Signal generator C was set to have a 400 Hz audio tone with FM modulation and a deviation of +/- 24 kHz.
6. Signal generators B and C were set to output levels of -120 dBm.
7. Signal generator B was set to a frequency of fc – 400 kHz.
8. Signal generator C was set to a frequency of fc – 800 kHz.
9. The RF output levels of signal generators B and C were increased until the recorded SINAD level was reduced from 50 dB to 30 dB.
10. The RF power level on both signal generators was recorded on a spectrum analyser with a 30 kHz resolution bandwidth.

The above steps were repeated for frequency offsets of fc + 400 kHz and fc + 800 kHz on signal generators B and C respectively.

The squelch or gain/volume control was set to a mid-range value for the tests to represent typical operating conditions of a receiver.

Due to tone lock and digital encryption employed by some manufacturers, it was only possible to get results for two analogue receivers, shown in Table 6.2 below.

Table 6.2: Intermodulation levels for measured receivers

Receiver	Type	Interferer Rejection (dB)	
		Lower Band	**Upper Band**
1	Analogue Mid-range	52.00	51.61
2	Analogue Professional	56.92	57.11

All the results are above the interferer rejection limit of 35 dB specified in Draft ETSI TR 102 546.

6.8 Transmitter intermodulation measurements

The test set-up for transmitter intermodulation performance is shown in the figure below. Radiated measurements were performed in a fully anechoic chamber.

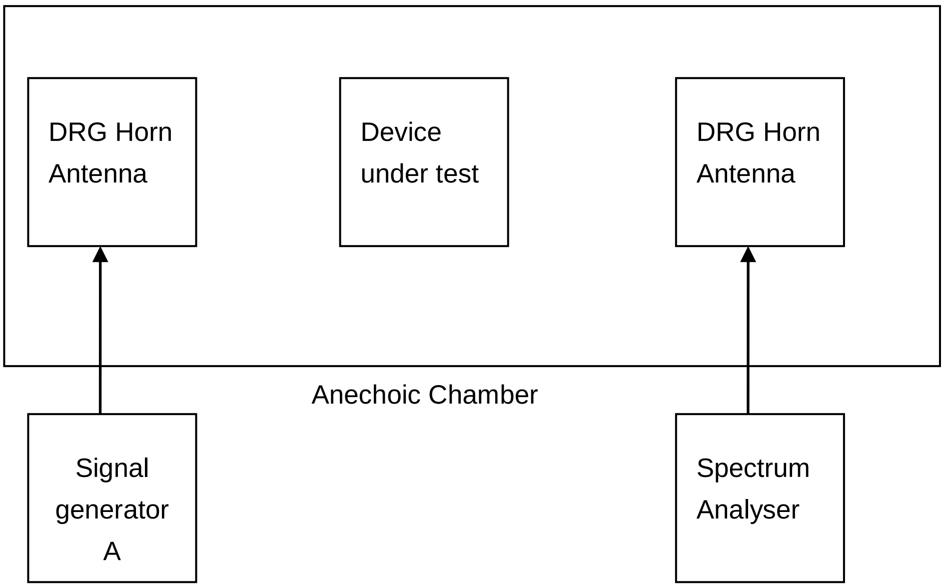

Figure 6.14: Test setup for measuring transmitter intermodulation/interferer level

The following test method was used to determine the intermodulation performance of three different PMSE transmitters:

1. The transmitter under test was switched on and placed in an anechoic chamber.

2. The frequency of the transmitter under test was recorded as fc. The output power was recorded on a spectrum analyzer.
3. Signal generator A was set to have an un-modulated CW RF output signal.
4. Signal generator A was set to a frequency of fc + 1 MHz with RF output level set to 0 dBm.
5. The RF output level of signal generator A was increased until equal to the power from the transmitter under test recorded in step 2.
6. The level of the intermodulation components at 2f1 – fc and 2fc – f1 were recorded on a spectrum analyzer.
7. The measurement was repeated with signal generator A set to a frequency of fc – 1 MHz.
8. The transmitter intermodulation attenuation was calculated as the ratio of the largest third order intermodulation component with respect to the carrier.

The results are shown in the table below.

Table 6.3: Transmitter intermodulation attenuation

Transmitter	Model	Type	Interferer Rejection (dB)
1	Shure U2	Analogue Professional	56.05
2	Sennheiser SK5212	Analogue Professional	52.85
3	Zaxcom TRX 900	Digital Professional	61.37

The results show that the digital transmitter has somewhatbetter intermodulation rejection performance than the two analogue devices tested, though there is no reason to believe that this need generally be the case.

6.9 Transmitter re-radiation separation distance test

Two further tests were carried out to analyse the intermodulation products generated by two analogue transmitters in close proximity.

6.9.1 Test 1- Anechoic chamber test

The first test shows how the IPs generated by two transmitters vary as the distance between them increases. The following test method was used:

1. Two transmitters, A and B, were placed in an anechoic chamber transmitting on frequencies 800.95 MHz and 801.6 MHz.

2. The transmitters were initially placed at a distance of 40cm apart and the resulting IP generated at 800.35 MHz was recorded using a calibrated antenna at a distance of 7m and a spectrum analyzer.

3. Step 2 was repeated for separation distances up to 2m in increments of 10cm.

The results of the measurements are presented in the figure 6.15 below.

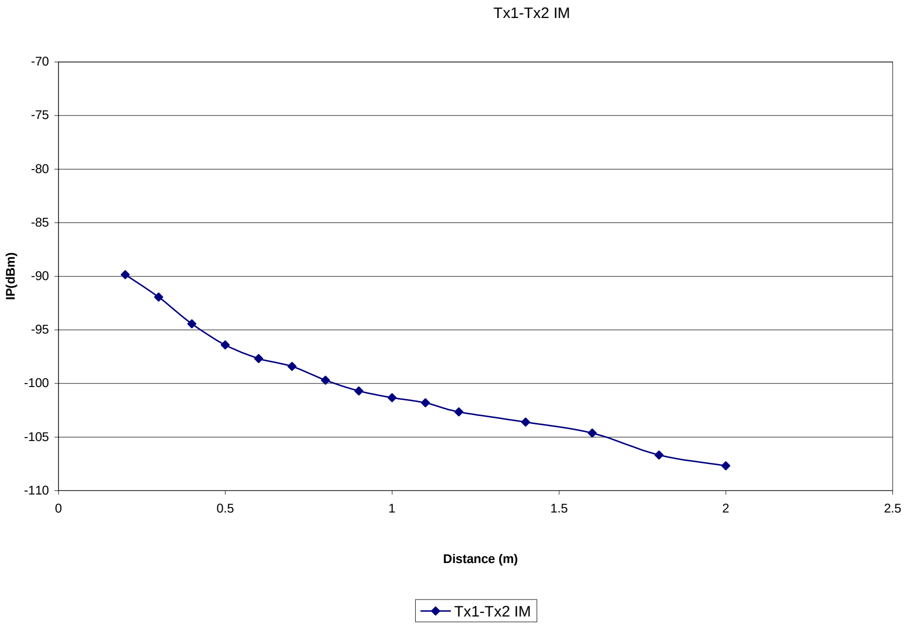

Figure 6.15: Plot of Intermodulation against transmitter separation

The results show that, as expected, the IP levels drop by around 6 dB as the distance between the transmitters is doubled.

6.9.2 Test 2- Radiated Carrier-to-Interference measurements

The second test shows the measured Carrier-to-Interference levels with an analogue transmitter operating on a frequency where a third order IP is present.

The set-up is shown in the figure below.

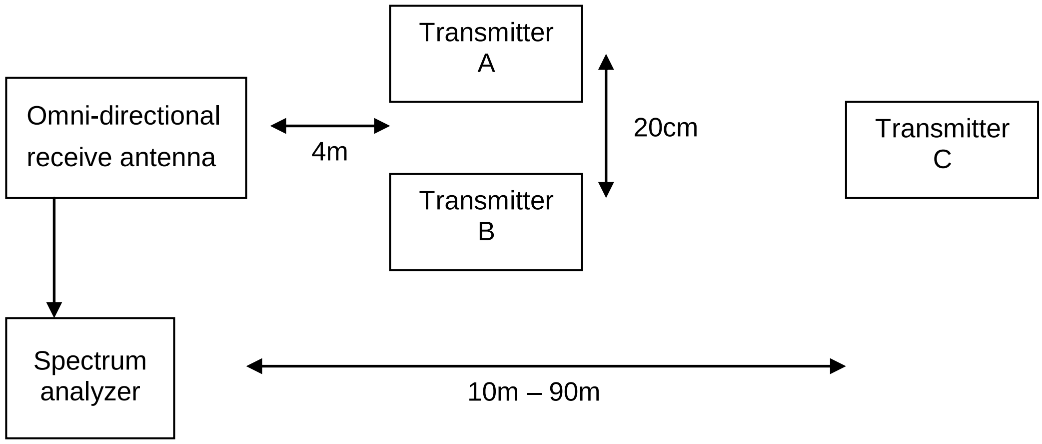

Figure 6.16: Test setup for Carrier-to-Interference measurements

The following test method was used:

1. Two transmitters, A and B, were placed 20cm apart representing a fairly worst case separation distance. Both transmitters were placed at 4m from the receiving antenna.
2. Transmitters A and B were set on frequencies 800.95 MHz and 801.6 MHz and the resulting IP level at 800.35 MHz was recorded on a spectrum analyzer.
3. Transmitter C was switched on and set to 800.35 MHz at a distance of 10m from the receiving antenna and the wanted transmit power (C) was recorded on a spectrum analyzer.
4. The distance between Transmitter C and the receiving antenna was increased in 10m steps up to a maximum distance of 90m and the wanted transmit power (C) was recorded at each step.
5. The resulting Carrier-to-Interference ratio was calculated from steps 2 and 4.

The results are shown in table 6.3 below.

Table 6.3: Carrier-to-Interference level against distance from receive antenna

Distance (m)	Measured level (C) (dBm)	C/I (dBm)
10	-49.81	39.69
20	-56.84	32.66
30	-59.12	30.38
40	-56.67	32.83
50	-62.67	26.83
60	-67.92	21.58
70	-67.28	22.22
80	-61.02	27.48

6.10 Summary & conclusions

In respect to the receiver sensitivity values published by the manufacturers of the equipments tested, the lab results matched up with the specifications shown in annex D. It should be noted that the gain/volume or the squelch levels set on the various equipment affects the minimum sensitivity of the receivers.

From figure 6.13 it can be seen that the digital receivers require between 4 to 11dB less co-channel protection than analogue receivers, making such systems significantly more tolerant of interference from all mechanisms (adjacent channel, intermodulation products, co-channel microphone and TV transmissions)

Receiver intermodulation performance was found to exceed the minimum requirement given in ETSI TR 102 546 and, for the limited samples tested, was found to be broadly in line with the performance stated by the manufacturers.

Transmitter intermodulation performance is dependent on several factors including the separation distances between the transmitters generating the intermodulation products as well as the type and make of transmitters. The one digital transmitter tested was found to have better intermodulation rejection than the analogue devices tested, by around 10 dB. One manufacturer of analogue transmitters, whose devices were not tested, is known to include circulators in the transmitter output, which should usefully reduce the level of re-radiated intermodulation. An alternative approach, adopted by another manufacturer of analogue equipment, is to include an attenuator in the transmitter output, to protect against the generation and re-radiation of IPs (at the cost of a loss in transmitter power or battery life). Any such reduction in re-radiated IPs will have a significant impact on spectrum efficiency, and should be strongly encouraged.

7 FIELD TRIALS

7.1 Introduction

Building on the lab measurements a series of tests were conducted at BBC Elstree Studios and The Brit Oval Cricket Ground. These tests used Zaxcom digital and Sennheiser Analogue PMSE equipment.

7.2 BBC Elstree television studio

7.2.1 Digital

For the purpose of these measurements the digital PMSE equipment was set up on Channel 66 (830 – 838MHz). The transmitters/receivers were tuned with 16 channels occupying the 8MHz block. The transmitters were moved around the vicinity of the receive antennas and a plot (Figure 7.1) was made capturing the maximum recorded levels. The span in this figure extends +/-8MHz from channel 66 to show the levels of IM products in the adjacent channels.

It should be noted that the due to the regular frequency spacing of the digital transmitters this is a worst case scenario in which the IPs generated fall directly co-channel with other transmitters, these are therefore not visible on the spectrum plot.

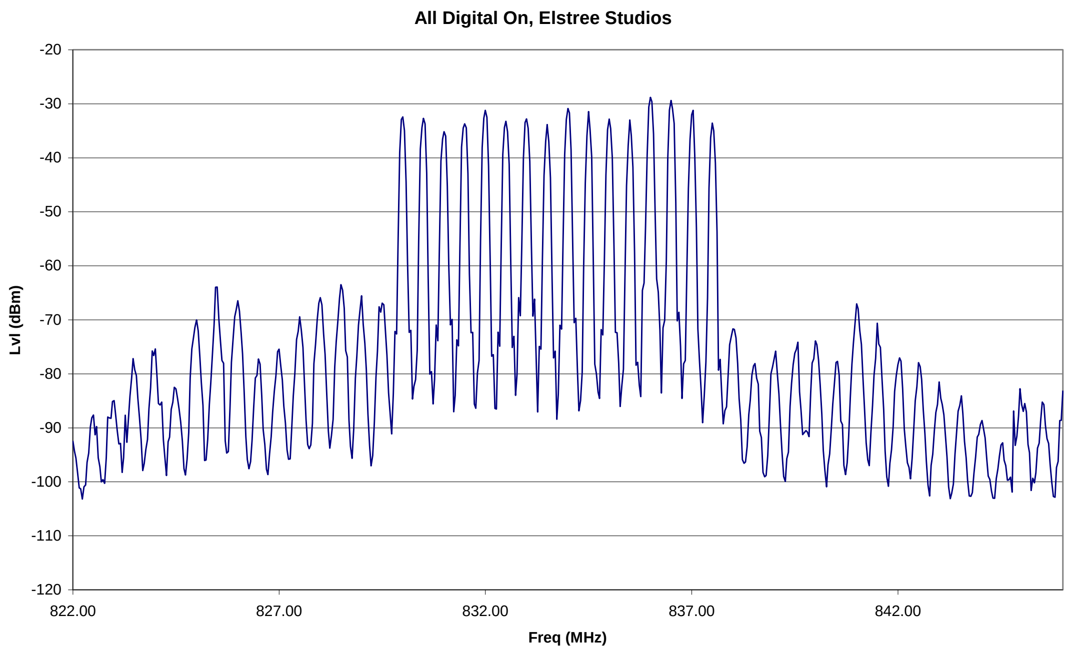

Figure 7.1: Plot of Spectrum with all 16 digital transmitters switched (Elstree)

Intermodulation products in the adjacent channels are clearly visible with levels as high as -35dBc recorded.

The BER data logged for the 16 channels showed that some bit-errors occurred whilst the transmitters were moved around, but that these were corrected by the system coding.

7.2.2 Analogue

For the purpose of these measurements the analogue PMSE equipment was set up on Channel 62 (798 – 806MHz). Measurements were made using 15 Sennheiser 5000 series analogue transmitters.

An optimal frequency plan for 15 transmitters was drawn up, as shown in Table 7.1.

Table 7.1: Analogue Transmitter Frequency Plan

Transmitter Identifier	Frequency (MHz)	Transmitter Identifier	Frequency (MHz)
1	798.1	9	802.4
2	798.45	10	803.95
3	798.85	11	804.85
4	799.3	12	803.525
5	799.8	13	801.925
6	800.35	14	805.375
7	800.95	15	805.675
8	801.6		

An initial measurement using 8 transmitters within a 4 MHz block of channel 62 was made to demonstrate IM products being generated across the 8 MHz channel, as shown in Figure 7.2.

It is important to note that if 8 transmitters were being used within channel 62 they would not be tuned to these frequencies; the frequency plan used here has been optimised for a total of 15 transmitters.

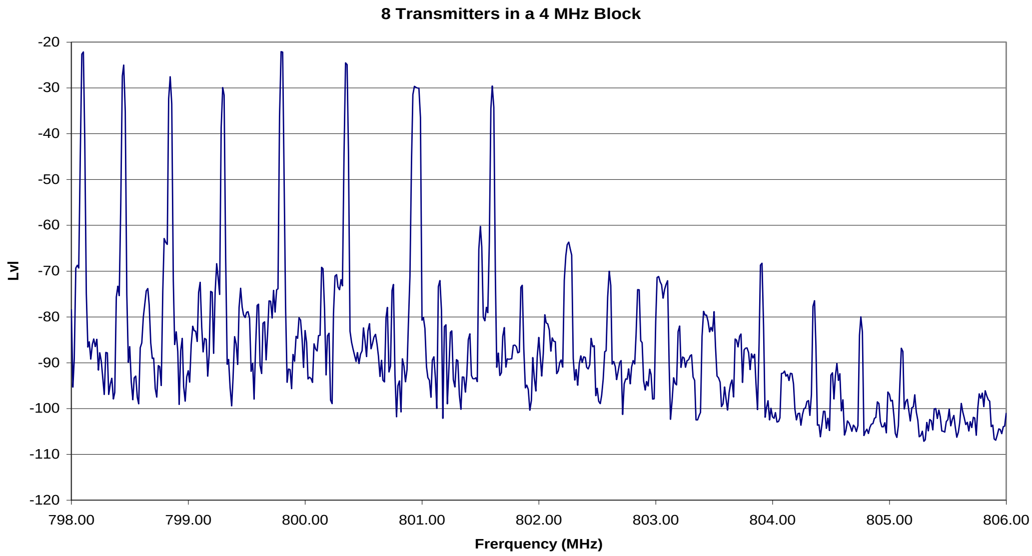

Figure 7.2: 8 Transmitters Operating in a 4 MHz block of Channel 62

Figure 7.2 shows that, with 8 transmitters spaced over 4 MHz, IPs of up to -30dBc were recorded.

Figure 7.3 below shows 15 transmitters operating in Ch62 and the associated IPs.

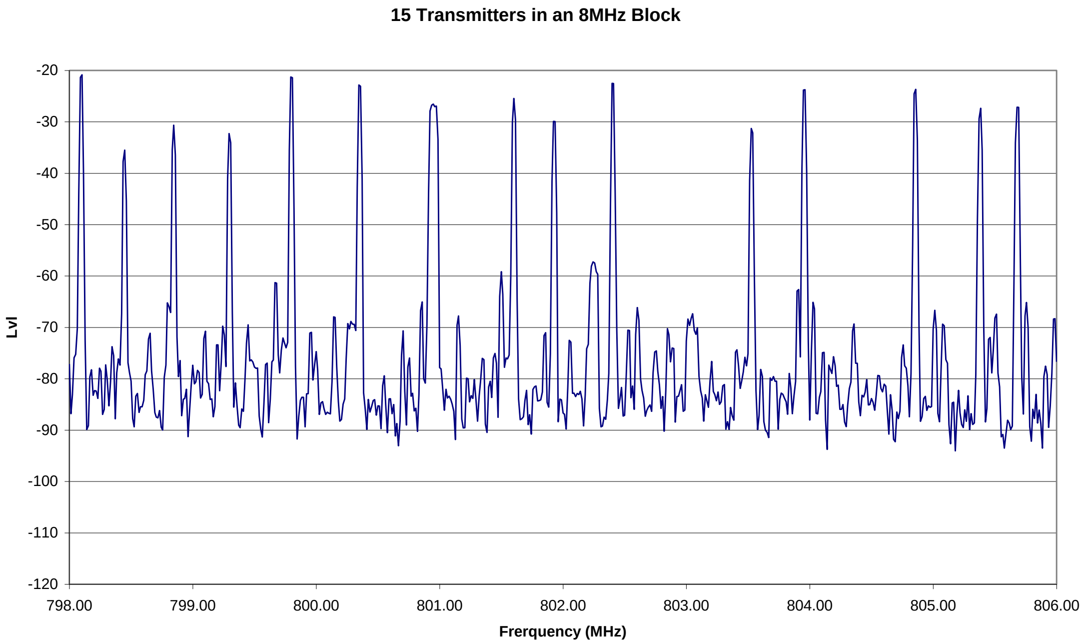

Figure 7.3: 15 Transmitters Operating in Channel 62

The figure below shows how the signal strength of a single transmitter varies with distance and time as the transmitter moves around the studio in an arc. The propagation effects on the received signal strength can clearly be seen.

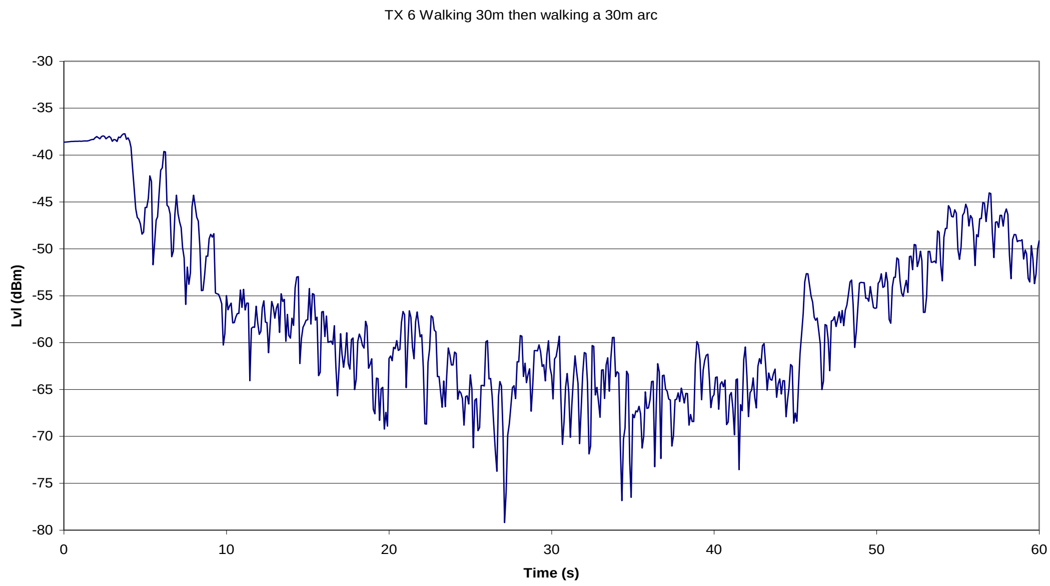

Figure 7.4: Received signal strength over time at Elstree Studios

7.3 Brit Oval cricket ground

Further measurements were made at the Brit Oval cricket ground, representing a large open sporting arena.

7.3.1 Digital

The transmitters/receivers were tuned with 15 channels occupying channel 66 and a 16th transmitter tuned to channel 68 and monitored as a ‘baseline’. The transmitters were moved around the vicinity of the receive antennas and the resulting received signal levels were recorded on a spectrum analyser. Figure 7.5 shows the IPs generated across channels 65 to 68.

It should be noted that the due to the regular spacing of the digital transmitters this is a worst case scenario. Some of the intermodulation products generated fall directly co-channel with other transmitters, and these are therefore not visible on the spectrum plot.

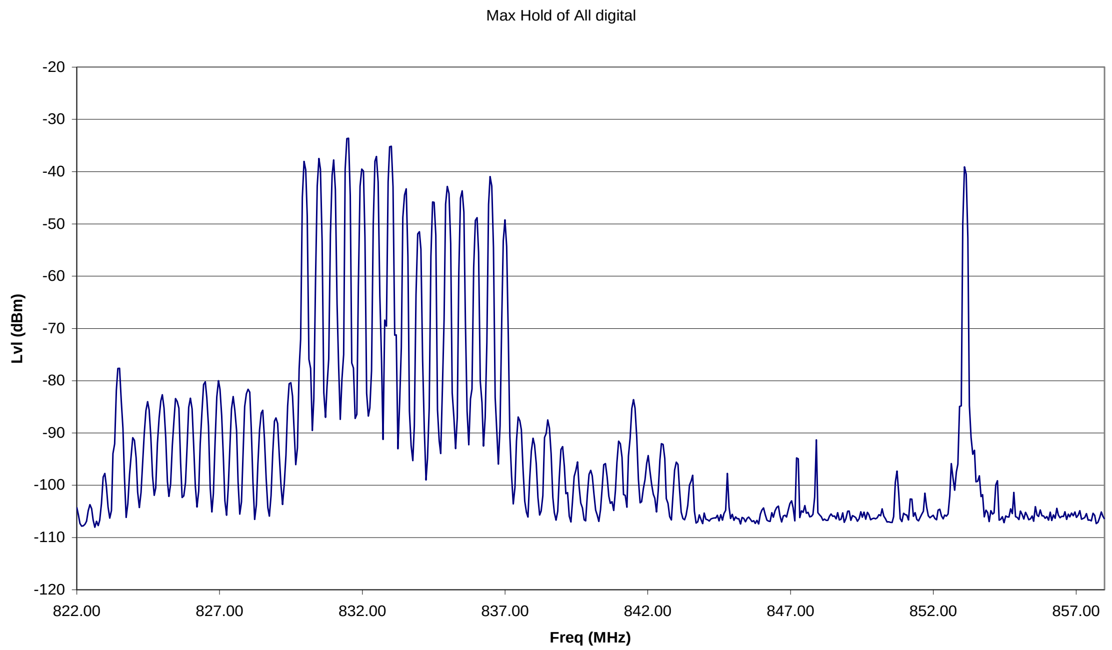

Figure 7.5: Plot of Spectrum with all 16 digital transmitters switched on

Intermodulation products in the adjacent channel are clearly visible with levels as high as -30 dBc recorded.

The BER data logged for the 16 channels showed that some bit-errors occurred whilst the transmitters were moved around but that these were corrected by the system coding. Data logged for the baseline transmitter shows that no error events occurred.

7.3.2 Analogue

Measurements were made using 15 Sennheiser 3000 and 5000 series analogue transmitters. These were tuned to an optimal frequency plan as shown above, Table 7.1.

The transmitters were moved around the vicinity of the receive antennas and a plot was made capturing the maximum recorded levels, as shown in Figure 7.6. The span extends +/-8MHz from channel 62 to show the levels of IM products in the adjacent channels.

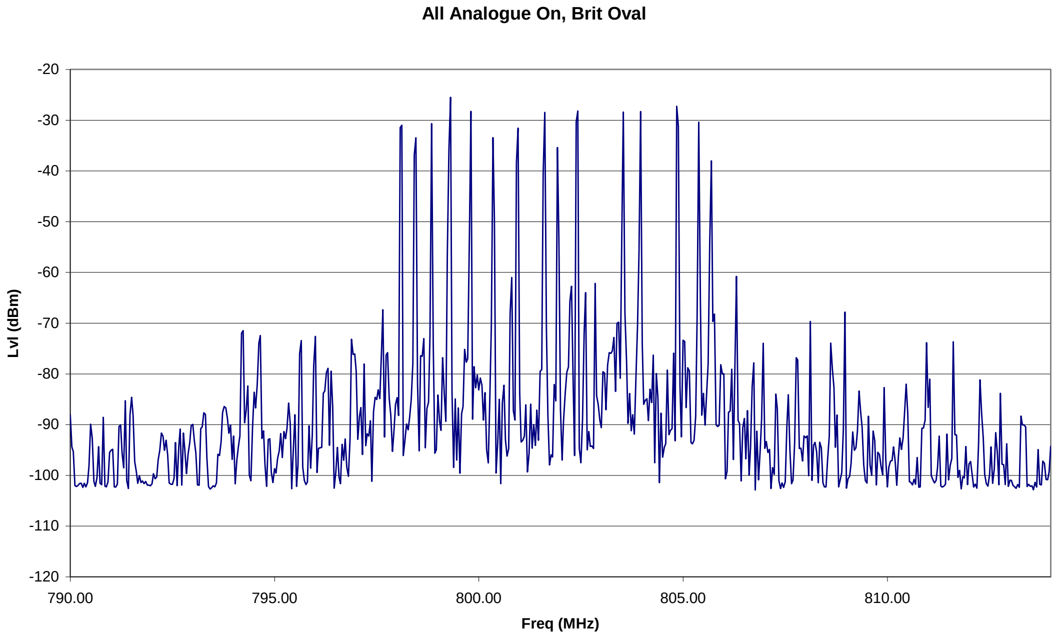

Figure 7.6: Plot of Spectrum with all 15 analogue transmitters switched on

Intermodulation products can be clearly seen throughout channel 62 with levels up to approximately -30dBc. There are also IPs in both adjacent channels with levels up to -40dBc.

The 15 transmitters operated with no tone and the noise floor was monitored to assess whether interference was detectable in the audio domain. Several noise errors were recorded during this test.

To further quantify the effects of IM effects a more specific series of measurements were made. Transmitters 7 and 8 were configured to produce a 3rd order IP on the same channel as transmitter 6. Three tests were then undertaken to analyse the effect of the IP on the wanted signal from transmitter 6:

1. Transmitters 7 and 8 were separated by 10cm, with transmitter 7 configured to transmit a 1 kHz audio tone. Transmitter 6 was then moved away from the receiving antenna until the IP level was sufficiently high for the tone to be heard on the receiver.

2. Test 1 was repeated with transmitters 7 and 8 separated by 50cm in order to determine the improvement in operating range as the IP level reduces.

3. Test 2 was repeated but with no tone on transmitter 7.

The resulting spectrum plots are shown in the figures below.

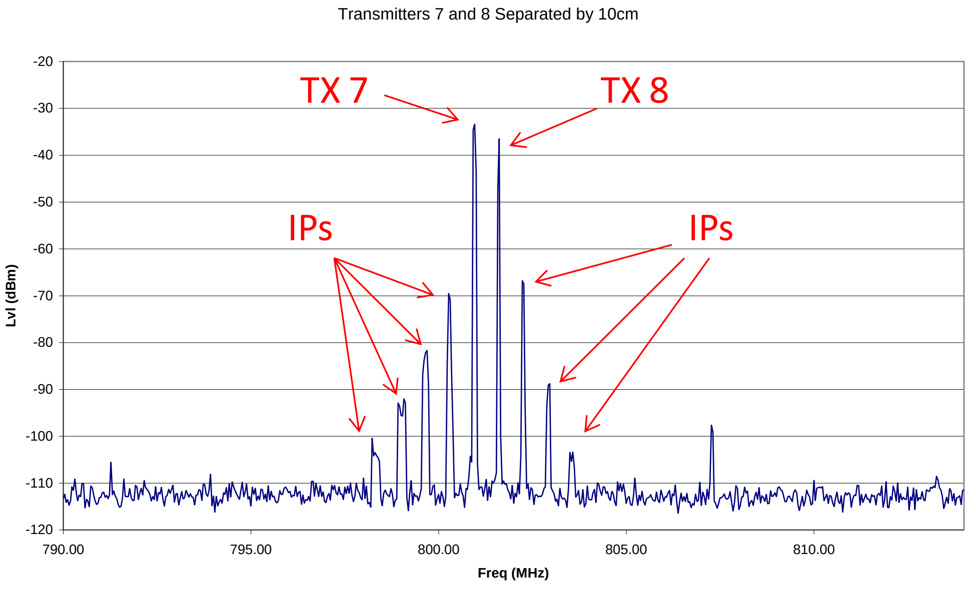

Figure 7.7: Transmitters 7 and 8 separated by 10cm with tone on 7

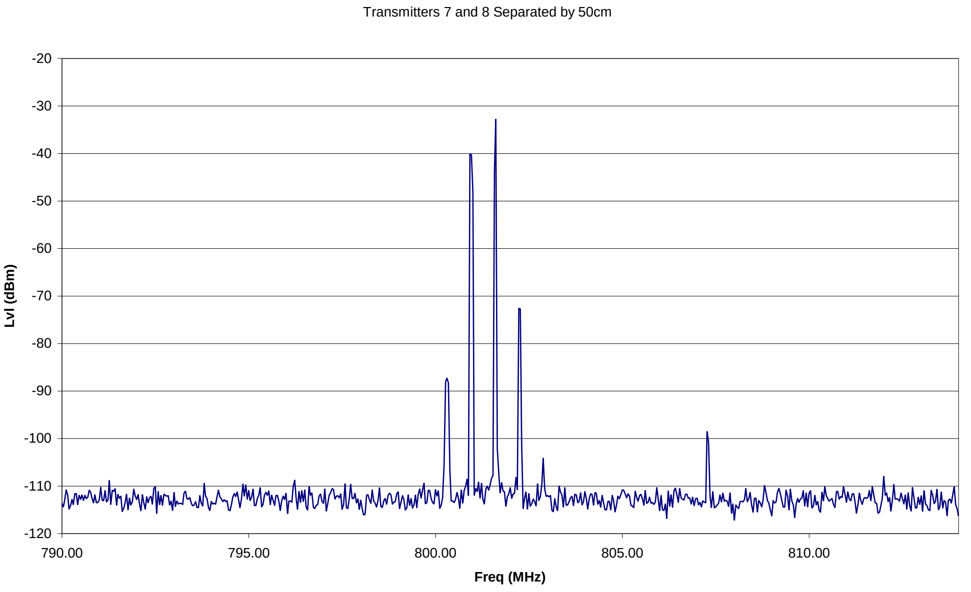

Figure 7.8: Transmitters 7 and 8 separated by 50cm with tone on 7

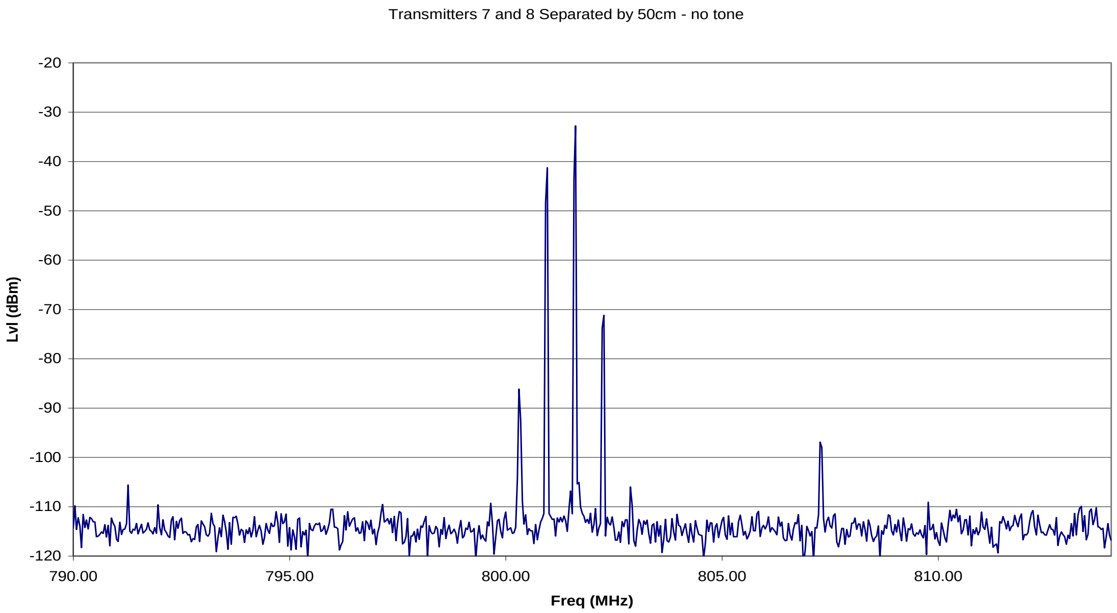

Figure 7.9: Transmitters 7 and 8 separated by 50cm – no tone

Comparing the above plots (Figure 7.7 to Figure 7.9) the differences in IM products due to proximity of the transmitters can clearly be seen. For a separation of 10cm the 3rd order IM product on the lower frequency side is -35dBc. Increasing the separation to 50cm reduces this IM product to around -45dBc.

The bandwidth of the IM product increases as a result of one of the transmitters being modulated with a 1 kHz tone. However, the power level of the IPs generated remains the same. This can be seen when comparing Figure 7.8 and Figure 7.9. Not only can this result in an IPs becoming co-channel with another channel but the modulation present on the IPs may be received as a wanted signal, demodulated and heard in the audio domain.

Figure 7.10 below shows the effect of the propagation environment at the Brit Oval on the received signal level from transmitter 6 as it moves around the perimeter of the stadium.

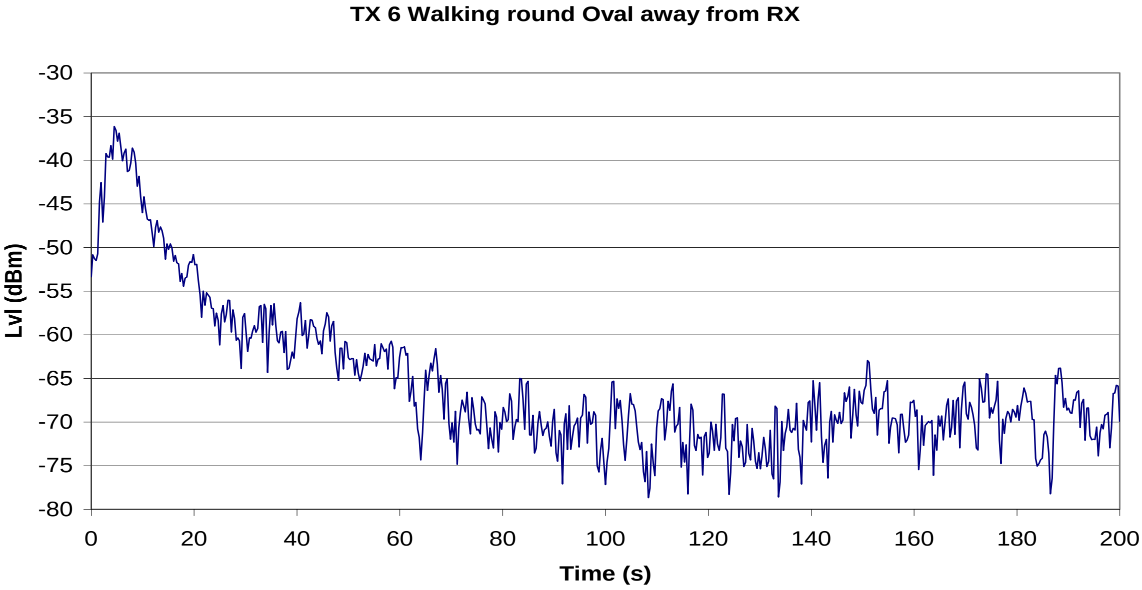

Figure 7.10: Received signal strength over time at The Brit Oval

Comparing the wanted signal level in Figure 7.10 to the IPs shown in Figure 7.7 – Figure 7.9 it can be seen that for various points around the Brit Oval the ratio of C/I falls below the point at which audio interference becomes noticeable at the receiver. With transmitter 7 modulated with a 1 kHz tone, the interference was manifested as an audible whistling effect on channel 6. With the tone switched off, the interference was audible as hissing and popping.

Testing at the Brit Oval showed that increasing the physical separation between two transmitters results in an increase in usable range between the victim transmitter and the receive antennas. Also the effects of an IP with modulation are more apparent as the audio content is demodulated within the victim passband.

7.4 Summary and conclusions

Field trials demonstrated that under controlled conditions and using an optimal channel plan provided by a supplier, 15 analogue channels can operate successfully. However, this requires the proximity of IP-causing transmitters to be carefully controlled. Digital equipment is more robust in the presence of intermodulation products, simply because the required C/I ratio for such systems is lower than that needed for acceptable analogue performance.

None of the field trials take into account operational conditions in adjacent channels, and a strong caveat must be given to the effect that, even where a high density can be achieved in a single channel, this density will not be possible in multiple channels. This limitation follows from the exponential increase in the number of IPs generated for each additional wanted carrier.

8 ASSIGNMENT CRITERIA

8.1 Introduction

To allow efficient and effective use of the available spectrum, it is important to specify assignment criteria for radio microphones that are both practical and appropriate; they should not be excessively conservative, but should provide the degree of protection required by the industry.

8.2 Previous studies and existing assumptions

The most significant recent work on this topic is contained in ERC Report 88 "*Compatibility and sharing analysis between DVB-T and radio microphones in Bands IV and V*" [2], and in the report prepared for Ofcom by Sagentia, "*PMSE: Future spectrum access*" [3].

The former report, published in 2000, was written in the wake of the Chester 1997 agreement on international co-ordination of interim DTT services, and the introduction of the first networks in the UK, Sweden and elsewhere. The report proposes sharing criteria for DTT and radio microphone systems.

The Sagentia report, published in 1998, formed part of the work undertaken in the "Digital Dividend Review", and adapted the ERC work to specific UK conditions.

Neither report was concerned with sharing *between* radio microphone systems.

In the discussion below, all calculations relate to a nominal frequency of 500 MHz, but may be scaled for other frequencies by applying a factor of 20 $\log_{10}(f/500)$ dB

8.2.1 ERC Report 88

8.2.1.1 DTT to microphones

This report firstly considers the case of interference *from* DTT transmitters *into* radio microphone receivers, assuming the same parameters used for planning of the Chester 97 agreement.

A value is determined for the interference field strength at the radio microphone receiver that must not be exceeded. Measurements made in the UK and Germany showed a required co-channel protection radio of 12dB.

This may seem a small value, but this is because most of the DTT power falls outside the microphone bandwidth. If all the DTT power fell in the 200 kHz microphone channel, this value would be closer to 28dB, which is comparable to the measurements made for microphone protection from narrowband (FM) interference given in Section 6, when allowance is made for the lesser impact of the noise-like DTT signal compared with modulated FM.

The FM-FM protection ratio figure is, however, associated with a criterion of 30dB SINAD, which would be considered too low for high quality broadcast use; it may be an appropriate criterion in the general context of wireless microphones, but this should be explicitly verified with users.

Combined with an assumed wanted field strength of 68dBuV/m from the microphones, the 12dB protection ratio gives a maximum tolerable interference level of 56dBuV/m (at 1.5m agl). For situations other than the co-channel worst case, the maximum tolerable interference increases, as shown in Figure 81.

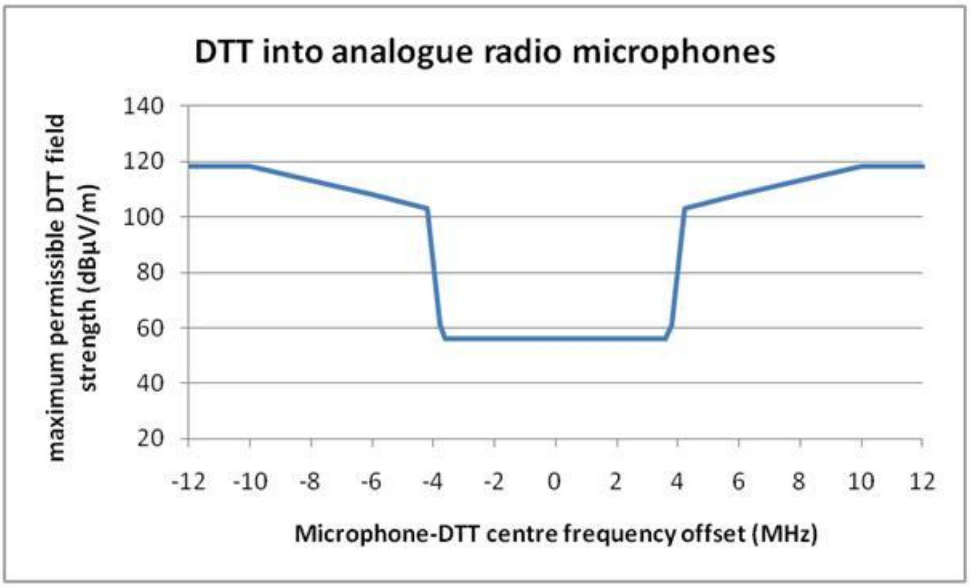

Figure 8.1: Tolerable DTT field strength at radio microphone receiver

The next part of the report applies a modified[10] version of the ITU-R 'Recommendation 370' propagation curves, to determine the necessary separation between the microphone receiver and DTT transmitters of different powers and heights. For a DTT site of 200W ERP, with 150m effective height, the separation required is around 11km (outdoor) and around 8 km (indoor).

Additional losses of 7 dB for microphone systems operating indoors, and 12 dB for propagation loss in urban areas are applied as necessary. Further predictions are also made, relating to the out-of-band DTT mask defined by PT21

During the measurements at Elstree, it was noted that the 200W DTT site at Hemel Hempstead uses channel 62, which has also been used by the BBC for radio microphones. No interference to indoor operation has been noted, but slight interference to outdoor operation was experienced when using directional aerials pointing towards the transmitter. The Hemel Hempstead transmitter is 13 km from BBC Elstree, so in this case the separation estimate made in Report 88 is of the correct order.

[10] Extrapolated to cover distances less than 10km

8.2.1.2 *Microphones to DTT*

The second part of the report considers interference *from* radio microphones into DTT receivers. The susceptibility of DTT receivers to interference was measured using a signal generator with 1 kHz tone at 40 kHz (UK measurements) or 70 kHz (German measurements) deviation. In the UK measurements the DTT system used 16QAM at -46 dBm and -52 dBm input, while the German measurements used QPSK/16-QAM and 64-QAM, all at 66dBm. The curve obtained from one set of the UK measurements is shown below.

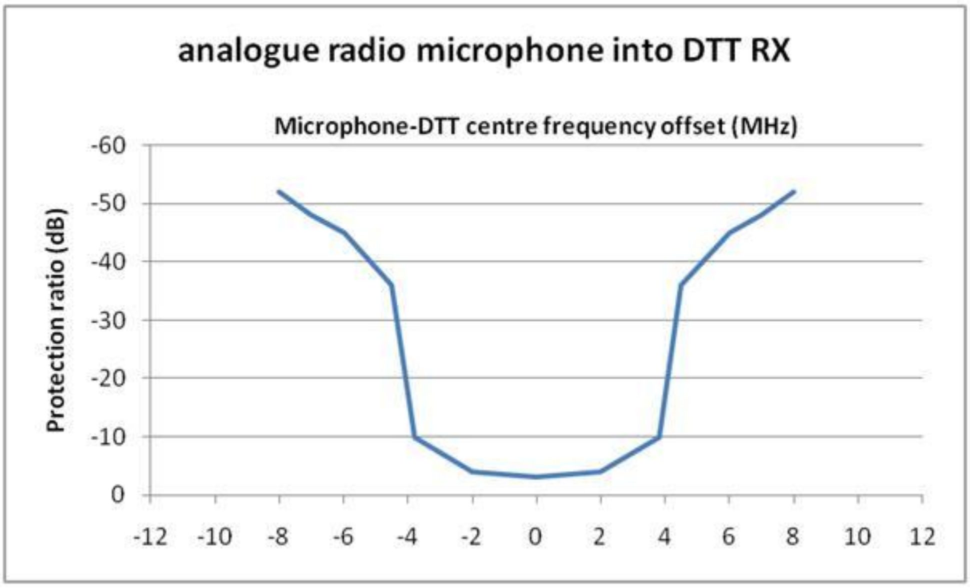

Figure 8.2: Protection ratio for interference to DTT

The co-channel value of -3dB is low because only a few of the DTT carriers are interfered with by the radio microphone signal (an FM transmission modulated at 1kHz to a deviation will occupy only approximately 82 kHz), allowing the receiver error correction to reconstruct an error free signal.

In predicting the impact to domestic DTT receivers, fixed reception was assumed, with a 12dBd aerial. The following assumptions are made:

Median FS (for 95% coverage of 16-QAM):	49dBµV/m (10m, 500 MHz)
Co-channel C/I requirement:	-3dB
Joint location variability[11]:	9dB or 13dB (<100m, >100m)

The maximum (median) interfering field strength at the DTT receiver is given by:

49 dBµV/m +3 dB - 13 dB = **39 dBµV/m**

[11] This assumes that the wanted and unwanted signals are fading independently, each following a log-normal distribution with a standard deviation of 5.5dB. For distances below 100m, no fading is assumed for the microphone signals. These assumptions are questionable.

It is assumed that the median ERP of the microphones will be reduced by body loss, thus a 50mW (17dBm) bodypack will lose 14dB and have an ERP of 3dBm.

As the propagation model ('ITU-R Recommendation 370') used above is intended for longer ranges, a new model was used which assumes free-space (distance^2) path loss to a range of 100m, a distance^3 law between 100m and 1km, and a distance^4 law beyond. The path losses obtained from this model are shown in Figure 8.3, below.

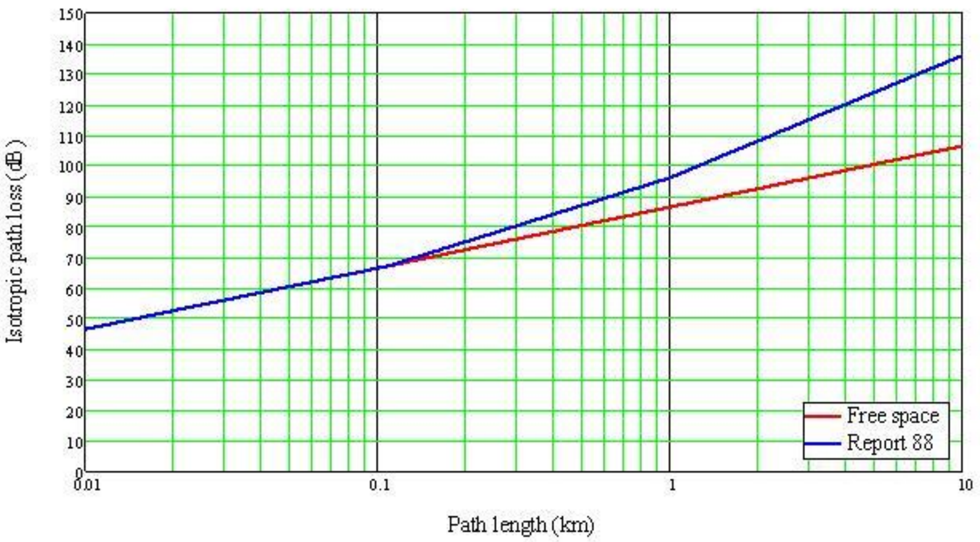

Figure 8.3: Propagation model assumed in ERC Report 88 (at 500 MHz)

Combining the assumed microphone power, the 39 dBμV/m criterion and the propagation model gives separation distances required for different frequency offsets between the microphone and the DTT channel. For the co-channel case, a distance of 950m (outdoor) or 550m (indoor) is obtained.

Having developed this model, the Report makes the following observation: "*For co-channel operation separation distances in the region of 1 km are necessary. The distance depends on the frequency band and type of radio microphone operation. In practice, distances above 1 km will not be acceptable in most cases. Therefore, in many cases co-channel operation in the same area is not possible*". Is seems surprising that a figure should arrived at, but then, apparently, disowned. It was, perhaps, partly in response to this uncertainty that Sagentia re-examined the topic.

8.2.2 Sagentia report

The report "*PMSE: Future spectrum access*" is a supporting document for the main output of this project, a set of maps showing the availability of UHF channels for radio microphone use in the UK.

This work took the ERC report as its starting point, but re-examined, and improved on, a number of the assumptions made in the earlier work. Once again, both interference from and into radio microphones was considered.

8.2.2.1 *Microphones to DTT*

For the case of interference into DTT, the minimum median DTT field strength assumed was aligned with the UK post-DSO planning assumption of 53.8dBμV/m.

Most significantly, it is noted that the ERC report considers only interference from a single microphone in a DTT channel. In practice for most applications (TV production, stage shows), a number of microphones are generally assigned within an 8 MHz channel. Sagentia therefore made the worst-case assumption that the channel is fully populated with 40 microphones (40 x 200kHz = 8 MHz), and assume that such interference will be comparable to that from another DTT transmitter. The standard DTT-DTT protection ration of 19.8dB[12] is therefore applied. An additional 3dB is added to this figure to allow for existing intra-system interference in the DTT network.

Another significant omission in the ERC Report is that no account was taken of the receiver aerial directivity. A maximum figure of 16dB is assumed in UK planning, and Sagentia assert that, if no microphone allocations are made within the transmitter service area, this directivity will always be available.

The new interference limit applicable at a domestic TV aerial is, therefore:

53.8 dBμV/m - 19.8 dB -3 dB - 13 dB + 16 dB = **34 dBμV/m**

This is broadly comparable with the Report 88 figure, as the increase in protection ratio is partly offset by the assumption of receiver aerial directivity.

The same piecewise propagation model is used as in the ERC report, with the same 7dB allowance for indoor operation. In addition, a 12dB additional loss is assumed in urban areas.

It is stated that this method predicts a necessary separation distance of 1.4 km (outdoors) and 0.9 km (indoor) for rural locations. Aegis calculations give slightly different values of 1.45 km (outdoor) and 960 m (indoor).

8.2.2.2 *DTT to microphones*

Sagentia applied the Report 88 method without change, using the 68 dBμV/m figure for microphone protected field strength at 1.5m and a 12 dB protection ratio.

8.2.3 Commentary

The assumption of multiple entries from radio microphones into a DTT channel seems to be a necessary improvement on the ERC Report 88 method. However, it may be that the method as published contains an error.

It is reasonable to suppose that, to a first approximation, the effect of 40 microphones evenly spread across an 8 MHz bandwidth will have a similar interference impact to a DTT signal. However, it seems that, when the model is

[12] This is the figure assumed in the UK planning process. See [1]

applied to generate the example given in the paper, the microphone power used is assumed to be that appropriate to a single interfere, i.e. 3dBm.

For the method to be consistent, it would be necessary to apply the total microphone ERP falling in the DTT channel, 40 x 50mW = 2W (33 dBm) minus the assumed body loss of 14 dB, giving 19 dBm.

If the separation distance is re-evaluated under these conditions, figures of 3.2km (outdoor) and 2.2 km (outdoor) are obtained.

A number of more minor issues might also warrant attention; none of these are errors as such, but rather relate to judgments of what simplifying approximations are appropriate.

- Polarisation discrimination: This is not mentioned in either report, and it is probably correct to ignore it as, in most situations, multipath effects and aerial positioning will mean that any discrimination is irrelevant. There may, however, be some value in applying a correction for the specific case where interference from a horizontally-polarised main TV transmitter is entering a fixed, directional radio microphone receive aerial, which will be vertically polarised.
- Location variability: The 13dB correction applied by Report 88 and Sagentia is probably an appropriate and pragmatic value. It is, however, worth noting that it is hard to justify theoretically. Firstly, it conflates the variability in field strength between different DTT receive *locations* and the *temporal* variability on the microphone-domestic aerial path. Secondly, the expression used assumes that5 both signals are log-normally distributed. This is probably true for the distribution of DTT signals found at rooftop locations over a modest area, but the fading on the obstructed microphone path is likely to follow a Rayleigh distribution. Finally, the correction is evaluated to give protection for 95% locations (or time), but this figure is not justified (though it may well be appropriate. Moving to a 90% value would reduce the correction by 3dB, increasing it to 99% would increase the correction by 5 dB.
- Microphone protected field strength: The author has been unable to find the origin of the 68 dBμV/m figure assumed for this (it was used in the Chester 97 agreement). The value seems rather high, especially as no further allowance is made for Rayleigh fading on the microphone channel. Perhaps by coincidence a transmitter with an EIRP (not ERP) of 50mW gives rise to a 68 dBμV/m if 14dB body loss is assumed. An alternative proposal might protect a Rayleigh fade of [20dB], giving a **48 dBμV/m** PFS. This would imply a separation of ~40km from a 1kW DTT transmitter, or 20km from the 200W example used above.
- Body loss: It is probably unrealistic to assume that this can be represented by a fixed reduction in transmitter ERP; there may be many occasions when

the full ERP will be ‘seen’ by the victim. A log-normal distribution of this loss, as assumed for the joint path loss statistics is probably more appropriate.

8.3 Microphone-microphone interference

While assessments of the mutual risk of interference with DTT are necessary to determine the ‘pool’ of microphone frequencies available in an area for allocation by a band manager, it is also necessary to understand the potential for interference *between* microphone systems to allow operation allocation of frequencies to different users.

The starting point for the development of assignment criteria must be protection ratio measurements between microphone systems, such as those reported in Section 6.6 of this report. These measurements show a required co-channel protection ratio of 25dB for analogue systems, with a 10dB relaxation in the case of mutual interference between digital systems. As noted above, it may be necessary to confirm that the specific measurement conditions for the analogue case are appropriate across the industry.

8.3.1 ‘Chester agreement / Report 88’ approach

If the ‘revised’ protected microphone field strength of 48 dBµV/m is assumed (allowing for 20dB of multipath fading on the wanted link), and the 24dB protection ratio applied, it is necessary to ensure that the interfering field strength is less than 24 dBµV/m.

If the interferer is assumed to be a 50mW transmitter with 14dB body loss (but see the last comment in Section 9.2.3), the ERP will be 3 dBm.

Assuming the piecewise propagation model, the suggested limit will be met for separations beyond 2.6 km. For indoor use, this falls to 1.8 km. If the 12 dB ‘urban correction’ is also applied, these values fall to 1.3 km (outdoor) and 900 m (indoor)

As noted in Annex C, the piecewise propagation model may significantly underestimate path loss if it is assumed to relate to median conditions, and, as 20dB of multipath fading has been allowed for, these distances should be significantly smaller.

8.3.2 Alternative approach

The sensitivity measurements described in Section 6 relate to an audio signal-noise level (50dB A-weighted) that is likely to be unacceptable for broadcast use. It seems appropriate, therefore, to protect a level some [10] dB above this figure, and a blanket value of -90dBm at the receiver input is tentatively assumed.

Most receiving systems will suffer additional losses due to antenna distribution splitters and feeder cables. Although they may be compensated for by the use of amplifiers and directional aerials, an extra 5dB is allowed for these losses.

The maximum range associated with these assumptions can be estimated if the following assumptions are made:

- The wanted signal is suffering a 20dB multipath fade
- The ERP of the microphone is reduced to 3dBm by body loss
- The two effects above are additive to an otherwise free-space (d^2) path loss

These assumptions give a maximum range of 150m

The value of -85dBm equates (at 500 MHz) to a field strength of 46dBμV/m, similar to the value more arbitrarily assumed above.

In calculating separation distances it may not be appropriate to include the ERP reduction due to body loss for the interfering microphone, as there will be many situations where this is not available. A separation distance is then required that results in an interfering power of -85dBm - 24dB = -109dBm.

In this case, the free-space assumption will certainly not be applicable, and the piecewise model is therefore applied (with the reservations noted in Annex C). This gives a separation distance of 6.4km, falling to 3.3 km for the urban case and 2.1 km for the urban, indoor case.

A more realistic model may be that proposed in Annex C, which, for a ‘suburban, outdoor’ case will give a separation distance of 1.1 km.

8.4 Conclusions

It is recommended that a more coherent and rigorous approach be adopted to the determination of assignment criteria than is evident in methods based on the work in ERC Report 88. While the overall criteria developed in that report clearly have some acceptance within the industry, and seem plausible, it appears that this may be due to overestimates of interference in some parts of the method being compensated for by underestimates elsewhere.

The key recommendation is that a new assignment method should treat interference probabilities in an explicit way. At the moment, for example, no probability is attached to the 14dB assumed for body loss or to the path loss prediction in the propagation model. Where probability is explicitly considered (the 13dB joint fading allowance for DTT and the wanted microphone) this is based on an assumption (uncorrelated fading with a log-normal distribution and a standard deviation of 5.5 dB) that is not clearly justified.

It is proposed that a 95% availability figure would be an appropriate starting point for discussion. It may be found, however, that this imposes spectrum availability constraints that are considered to be practically unsustainable (i.e. the areas shown on the Ofcom/Sagentia ‘channel availability’ map would shrink. If this is the case, then the existence of a more robust model with an explicit trade-off between reliability of performance versus availability of spectrum would be worthwhile.

9 CONCLUSIONS

The evidence regarding the use of more than eight frequencies per 8 MHz channel *appears* to be conflicting. Some respondents report using 14-16 microphones (digital or analogue) in one 8 MHz TV channel, while in other cases a maximum of 8 is adhered to. It seems, however, that the different cases partly reflect different attitudes to acceptable risk (i.e. a very low risk of interference may be tolerable in a live theatre production, but some interference can be accepted in the context of electronic news gathering). The density achieved is also related to the time, effort and expertise available to manage all aspects of RF engineering, production and stage management. Finally, the local environment is also important; thus, in the National Theatre, where only 8 microphones/MHz are allocated, there is a high density of use in adjacent theatres and other local venues, which is considered to pose a significant interference risk.

The environment in which microphones are deployed will have a significant impact on overall spectrum efficiency, most obviously where indoor use provides isolation to and from other spectrum users, but also in terms of the local radio reflectivity (which will determine the severity of fading experienced by microphone systems) and the spatial separation that may or may not be possible between transmitters and receivers, and mutually between transmitters (determining the constraints due to intermodulation products).

Measurements made in the laboratory have generally confirmed the values published by the manufacturers of the equipments tested. Digital receivers have been confirmed as requiring between 4-11dB less co-channel protection than the analogue receivers.

Field trials demonstrated that under controlled conditions and using an optimal channel plan provided by a supplier, 16 channels of analogue equipment can operate successfully. Such operation requires careful control of transmitters' mutual proximity and operational range of a given victim channel. It transmitter separation can be maintained at >1 metre, and if the wanted signals are not allowed to approach the noise-limited edge of coverage, it is unlikely that any interference will occur. It must be emphasised, however, that if a transmitter density of 16 transmitters is achieved in one 8 MHz channel, this does not imply that the same density can be maintained as further transmitters are brought into use.

It is recommended that a more coherent and rigorous approach be adopted to the determination of assignment criteria than is evident in methods based on the work in ERC Report 88. While the overall criteria developed in that report clearly have some acceptance within the industry, and seem plausible, it appears that this may be due to overestimates of interference in some parts of the method being compensated for by underestimates elsewhere.

10 ACKNOWLEDGEMENTS

Aegis and Cobham wish to acknowledge the following individuals and companies for the assistance they provided during the course of the project:

Jules Silvester and Mark Waddell from the BBC

Sarah Gray from the Brit Oval

Andy Lilywhite and Dave Hawker from Sennheiser

Richard Ganley from Trantec

Better Sound Ltd

Orbital Ltd

A REFERENCES

[1] JPP/MB/1 Version 2, 4 July 2003, Technical Planning Parameters and Algorithms

[2] ERC Report 88, "Compatibility and sharing analysis between DVB-T and radio microphones in bands IV and V",Naples, February 2000

[3] "*PMSE: Future spectrum access", Report for Ofcom by Sagentia Ltd, March 2008*

[4] "*Predicting path loss between terminals of low-height*", Report for Ofcom by Red-M et al, 2007, available at:

[5] "*Proposed addition to Recommendation ITU-R P.1411-3: Model for propagation between low-height terminals*", ITU-R Working Party 3K contribution, document 3K/165, 10 April 2007

[6] Constantinou, P, "*A new methodology for frequency coordination of wireless microphone systems over occupied TV-spectrum*" IEEE International Conference on Wireless And Mobile Computing, Networking And Communications, 2005. (WiMob'2005),

B TECHNICAL PARAMETERS

B.1 Radio microphone performance criteria

Analogue radio microphones use frequency modulation (FM) radio transmission. This has the potential to offer better immunity to noise and interference in comparison with amplitude modulation (AM).

B.1.1 Amplitude modulation

For an AM system, the signal to noise ratio (S/N) at audio frequency (AF) is simply related to the signal to noise ratio at RF by:

$$\frac{S}{N_{af}} = \frac{S}{N_{rf}} - NF_{rx}$$

where NF_{rx} is the noise figure of the receiver. An audio S/N figure of around 60dB is broadly representative of the level that is just perceptible under quiet listening conditions, and receiver system noise figures will typically be around 3 dB, giving an RF signal-to-noise ratio requirement of around 63dB. From the bandwidth of the system, the minimum receiver input signal can then be calculated. For a system intended to transmit audio, with an effective noise bandwidth of b = 15 kHz, the RF noise power (in dBm) is given by[13]:

$$N_{rf} = 10.Log_{10}\,(k.T.B.10^{3})$$

$$N_{rf} = -132.2 \text{ dBm}$$

The RF signal required to give an acceptable AF signal-noise ratio is then in the order of **-69.2 dBm**.

B.1.2 Frequency modulation

In an AM system, the modulated bandwidth cannot be greater than the modulating frequency (it is said that the 'modulation Index', MI, is limited to unity). This is not the case for FM, where the deviation can be increased arbitrarily, if spectrum planning allows. Such an increase leads to an improvement in audio S/N proportional to the modulation index, given by the ratio of frequency deviation to modulation frequency (f_d / f_m). For a radio microphone system with a maximum deviation of 45 kHz, and a maximum modulating frequency of 15 kHz, the modulation index is 3.0.

[13] K is 1.38 x 10^{-23} J/K, T is local temperature in Kelvin, typically 290K

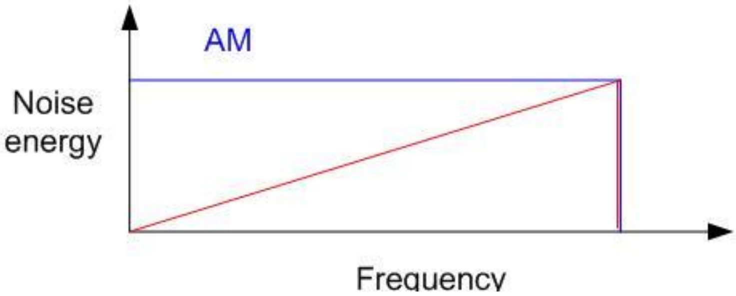

Figure B1: Noise spectra in radio systems (source: Aegis)

A further improvement results from the fact that the audio noise from an FM demodulator has a triangular, rather than rectangular spectrum, giving a further 4.5dB improvement. Finally, most FM systems make use of 'pre-emphasis', to boost the higher audio frequencies at the transmitter, with a corresponding de-emphasis at the receiver. This can confer an additional 4 dB of S/N improvement.

For the FM system, therefore, the audio S/N is related to the RF value by:

$$\frac{S}{N_{af}} = \frac{S}{N_{rf}} - NF_{rx} + 20\ log_{10}(MI) + 4.5 + 4 \text{ (dB)}$$

For our example

$$\frac{S}{N_{af}} = \frac{S}{N_{rf}} + 15 \text{ (dB)}$$

Leading to an RF input power requirement of -132.2 + 60 -15 = **-87.2 dBm**. The exact value adopted for system planning will depend on the exact weighting curves chosen (see below) and on the particular application.

B.1.3 Companding

A further improvement is possible in any system subject to noise, such as a radio channel or a tape recording system, by **com**pressing the input signal in terms of the range of amplitude it occupies, and ex**pand**ing it at the output of the system (thus *'companding'*). Well known examples are the Dolby systems associated with analogue tape recording, but the technique is universally applied to professional radio microphones.

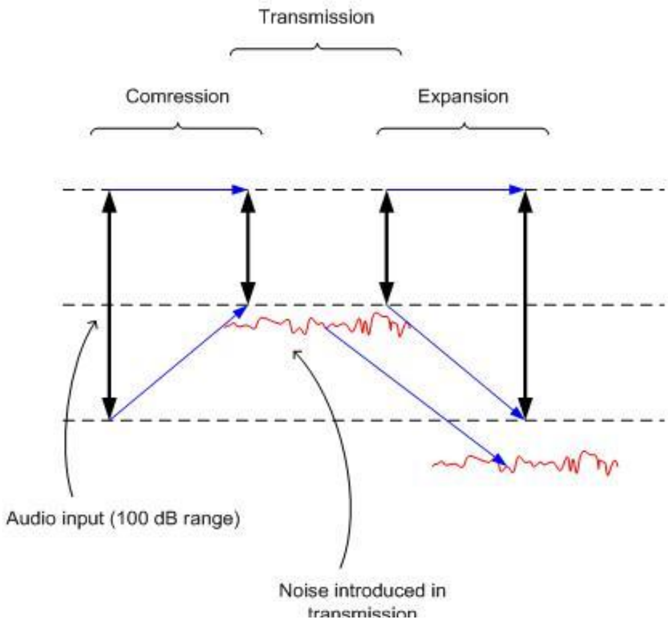

Figure B2: Audio companding system (source: Aegis)

The principle is shown in Figure B2, above. The input allows a very wide dynamic range (100dB), as often required in professional sound systems, but compresses this to a much smaller range for transmission. In the example, the transmission channel noise is at around -60dB, but when the signals are expanded at the receiver, this falls to -120dB (a figure that will be below the noise in the remainder of the system).

The penalty to be paid for the benefits of companding is a degree of distortion, mostly associated with the finite response time of the gain control circuits. Performers and sound engineers have, however, come to accept this to such an extent that (anecdotally alt least) manufacturers are working to replicate these effects in digital system which would, otherwise, be capable of more 'transparent' sound.

B.2 Noise and weighting

In the majority of microphone system specifications, signal to noise figures are quoted using an 'A-weighting', generally indicated by a value expressed in dB(A).

This is an attempt to adjust the measurement of noise so that it accord more precisely with the subjective effect on the human ear, which is less sensitive to noise at the highest and lowest frequencies.

The A-weighting curve, developed on the basis of audibility of pure tones, has been criticised for underestimating the impact of noise signals at frequencies between around 3-9 kHz. The more recently-developed ITU-R Recommendation BS.468 curves are generally considered more appropriate for this use; this weighting, however, leads to S/N figures lower than the A-weighted versions and are therefore seldom quoted on manufacturers data sheets.

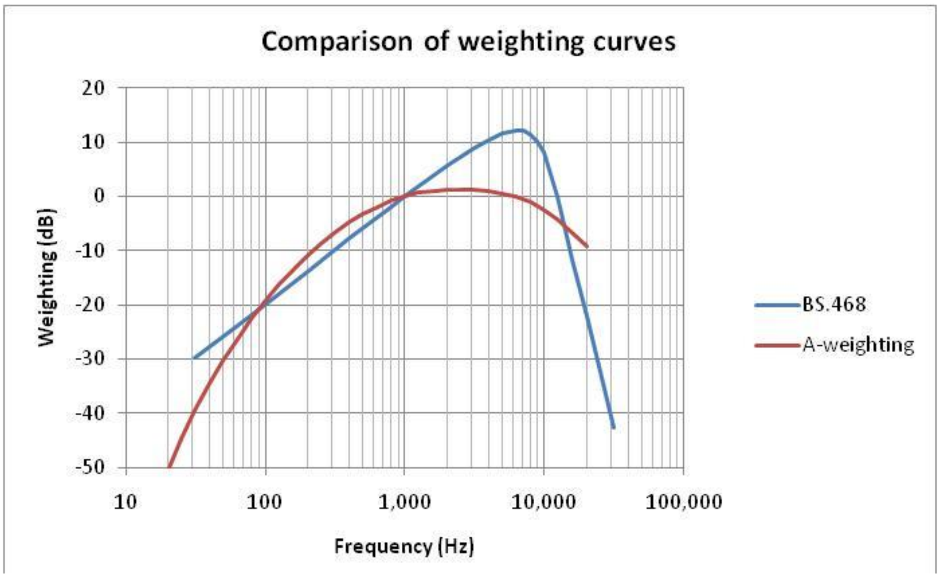

Figure B.3: Noise weighting curves

It should be noted that neither weighting curve may be strictly appropriate for estimating the impact of interference between microphone systems, which will not, generally, resemble white noise.

C FIELD STRENGTH MEASUREMENTS AROUND VENUES

At both venues, measurements were made of the field strengths, in the vicinity of the venues, from radio microphone transmitters. In all cases, the transmitters used were belt packs.

At BBC Elstree, a number of 50mW transmitters were left running inside Studio D, and measurements were made around the site, both at fixed locations using a directional aerial at 10m height, and at 2m using a nominally omni-directional, vertically-polarised dipole while driving round the site.

The results of the 10m measurements are shown in Figure C1, below (the car park is at ~100m, while the other locations in Fig. C1 are between 150m and 180m from the transmitter site)

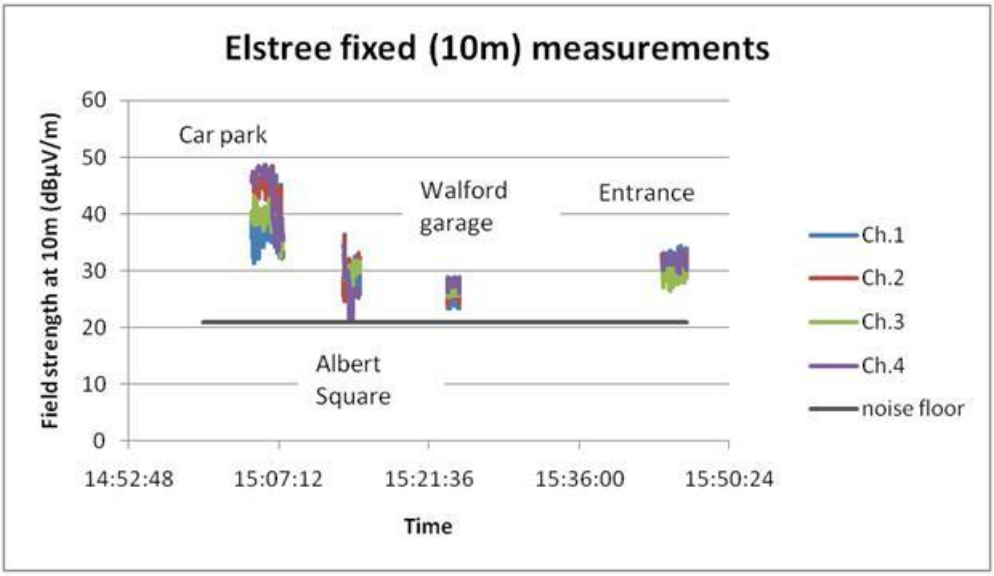

Figure C1: Field strength measurements at BBC Elstree

The mobile measurements are recorded in Figure C2. Unfortunately, the GPS receiver failed during these measurements, but the route took the vehicle from the 'Walford Garage' site to the 'Entrance', by way of a covered roadway running past the studio, and passing within some 10m of the transmitters.

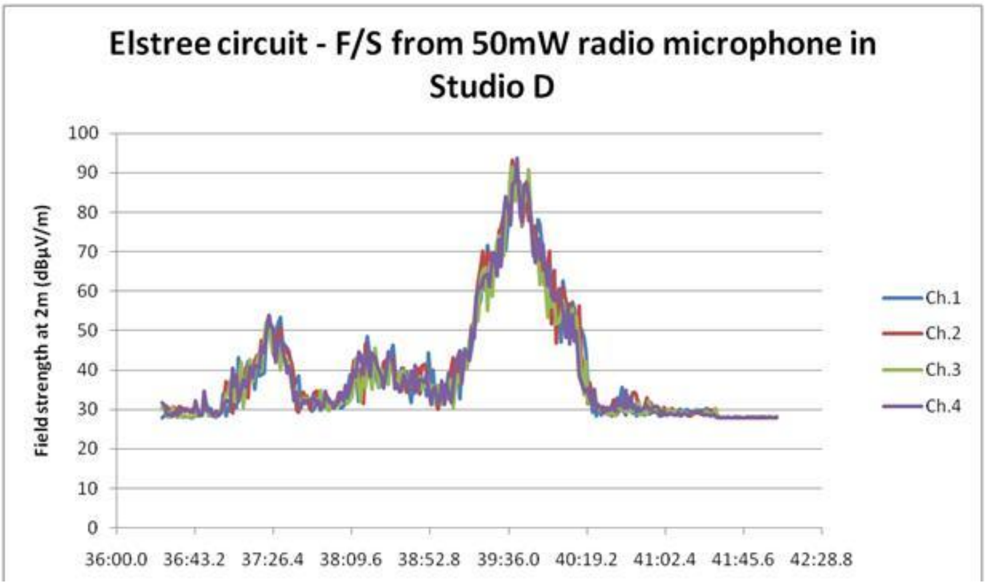

Figure C2: Mobile measurements at Elstree

At the oval a pedestrian measuring system was used, with a handheld sleeve dipole feeding a portable receiver driven by a laptop. As no GPS was available, position was logged by removing the aerial input as road junctions were reached; this had the benefit of also recording the noise floor of the receiver. The route followed is indicated in Figure C3.

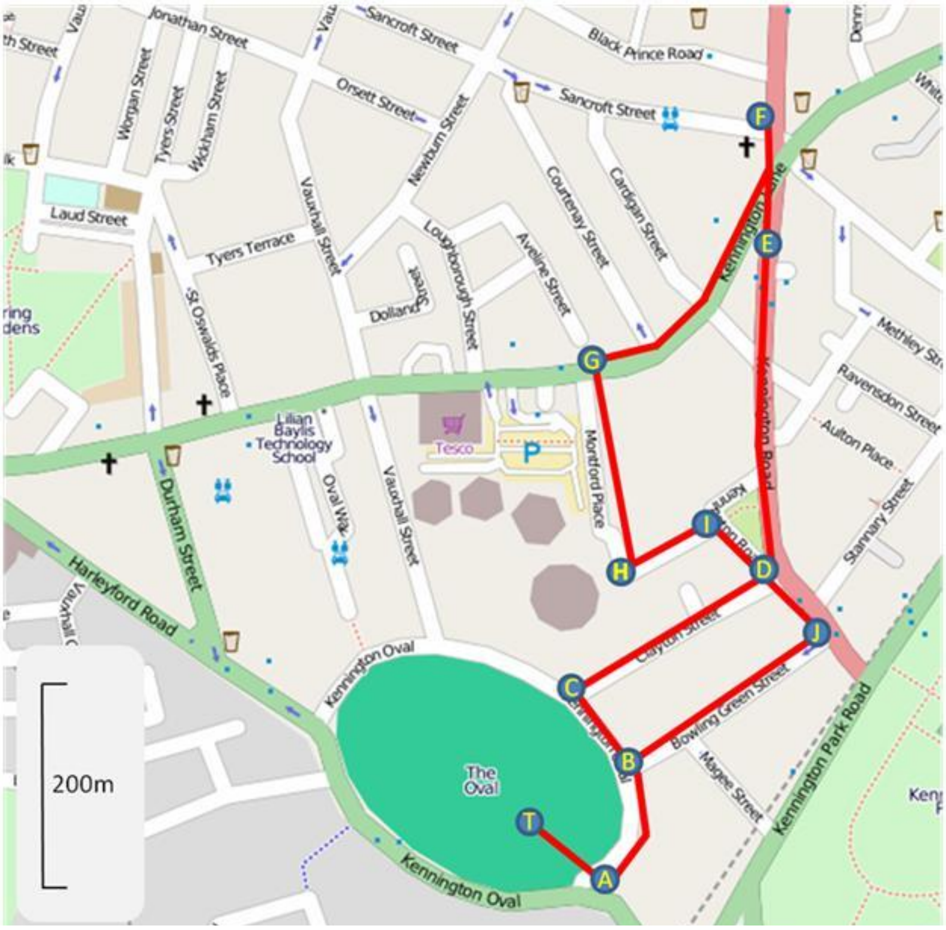

Figure C3: Route followed around Oval ground

Measurements were made of two active transmitters (Sennheiser SK5012) with a nominal ERP of 50mW. These were positioned at about 1m above ground, by the boundary fence of the Oval (i.e. on the edge of the grass, inside the stadium). A further channel, on which no transmitter was active was also monitored.

Figure C4 shows the field strength record that was obtained.

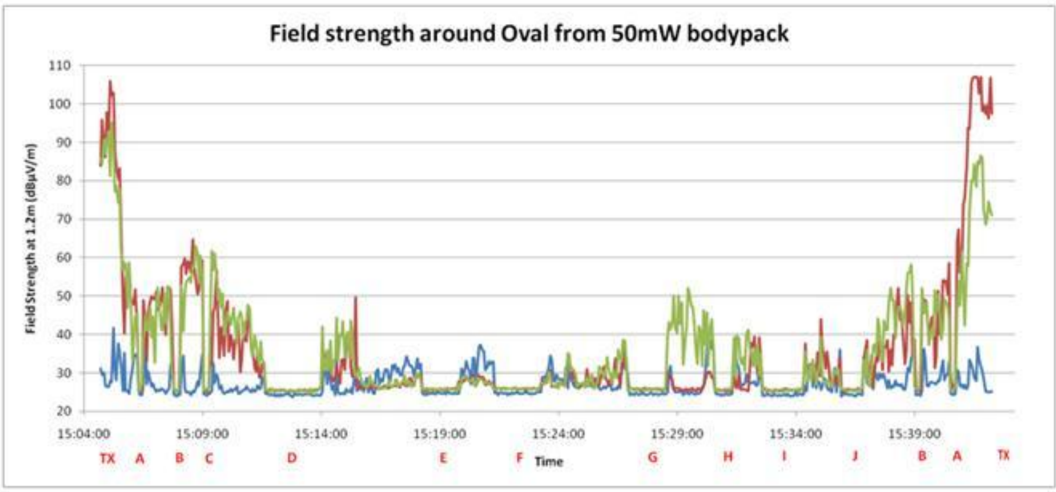

Figure C4: Field strength measured around Brit Oval site

The active transmitters are recorded by the red and green traces, while the blue trace represents the unused channel. At 400m range, between points 'D' and 'E', the field strength has fallen to around 30dBμV/m.

The 'unused' channel[14] shows signal levels up to 10dB above the noise level in several places; at the start and end of the run these will be IPs from the active transmitters, but the high levels around points 'E' and 'F' are unrelated.

It is useful to compare these measured results with the simple propagation model used in ERC Report 88, and in the Sagentia proposals. Figure C5 shows the field strength versus range from a 50mW ERP transmitter in different environments.

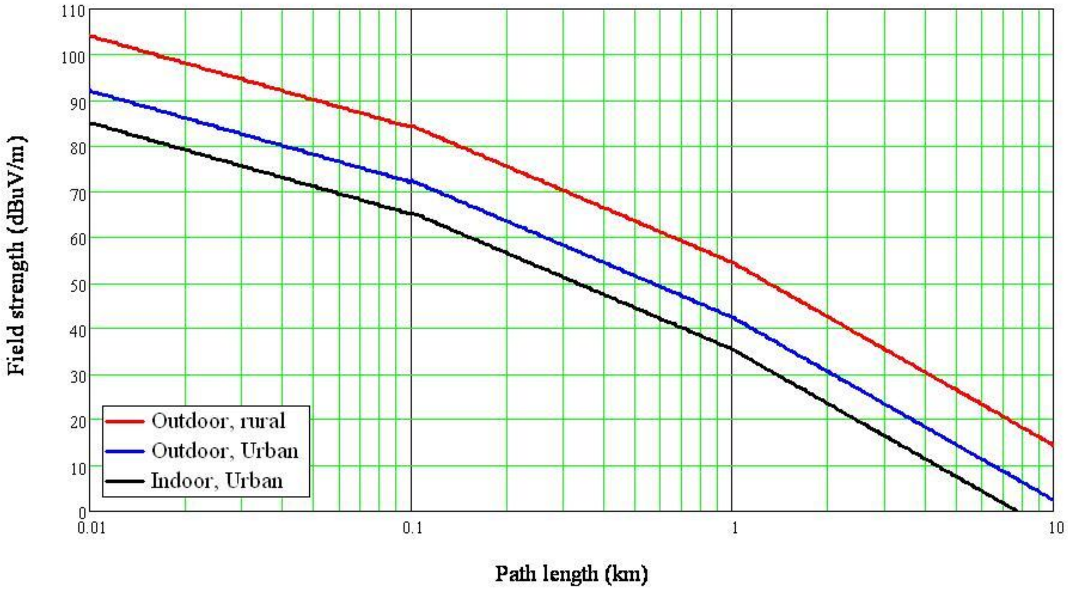

Figure C5: Piecewise propagation model: Field strength for 50mW ERP transmitter

It can be seen that, for the 'outdoor, urban' situation corresponding to the Oval test, the actual field strength is at least 25dB below that predicted. Similarly, if BBC Elstree is assumed to correspond to an 'indoor, urban' environment, the model predicts field strengths some 20-25dB too high. This degree of error is inevitable for such a simple model when compared with only a few data points and it might be hoped that a wider range of measurements would show the model to be more representative.

---

[14] The frequency was 798.1 MHz, at the bottom edge of channel 62.

The accuracy of the model cannot, however, be judged, as it is not stated whether the prediction is intended to relate to the median case (i.e. 50% of locations) or to a more extreme situation (i.e. the field strength that will be exceeded only in 1% of cases.

The latter may be exactly what is required in the PMSE assignment case, but this should be stated explicitly.

C.1 Alternative propagation modelling approach

For the application under consideration her, it is unlikely that a complex propagation model, relying on detailed input information (building database, terrain,l etc) would be justified.

There has, however, been a significant amount of relevant work undertaken recently on behalf of Ofcom, aimed at developing reliable statistical models for low-height, short-range propagation. This work has been submitted to ITU-R Study Group 3 and is described in [4], [5].

This model takes a statistical approach to describing path loss at short range in urban areas.

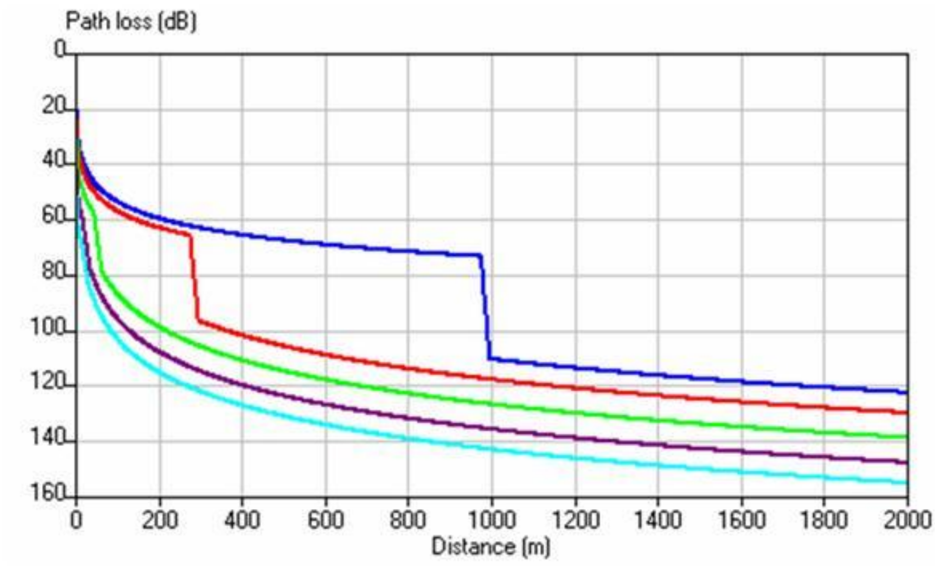

Figure C6: Curves of basic transmission loss not exceeded for 1,10,50,90 and 99% of locations (400 MHz, suburban) from [4]

Applying this model to be applied to the Oval case at 400m, gives a '50% location' value of 28dBμV/m, corresponding well to the measurements. The 28dBμV/m predicted by the piecewise model corresponds to a field strength that would only be exceeded at between 1 and 5% of locations.

D MANUFACTURERS' SPECIFICATIONS

D.1 Sennheiser EM 1046 Receiver Specification

Frequency range (Fe)	450 - 790 MHz with RX module item no. 03246 760 - 960 MHz with RX module item no. 03247
Bandwidth	24 MHz
Channel spacing, min.	300 kHz
Channel grid, min.	5 kHz
1st oscillator frequency (1st LO)	71 MHz below / above Fe
1st intermediate frequency (1st IF)	71 MHz
2nd oscillator frequency (2nd LO)	81.7 MHz
2nd intermediate frequency (2nd IF)	10.7 MHz
Deemphasis	50 µs
Nominal deviation/Peak deviation	± 40 kHz / ± 56 kHz
AF outputs	8 x XLR connectors with a balanced AF output signal, min. load impedance 600 Ω, 1 Sub-D-connector, 25 pins, with 8 unbalanced AF signals, min. load imp. 5 kΩ (option: decoupled and balanced, min. load imp. 10 kΩ)
Nominal audio level	+ 12 dBm
Peak audio level	+ 18 dBm
THD for peak deviation	≤ 1 % (typ. < 0,5 %)
Audio frequency range (+1 dB / -2 dB)	40 Hz - 20 kHz
Compander	HIDYN plus® (internally defeatable)
Diversity	RF signal-dependent selection of AF outputs
Squelch	adjustable threshold (0 - 100 µV RF input voltage)
S/N = 52 dB (unweighted, with HIDYN plus®)	≤ 1.5 µV (typ. 1 µV)
S/N max. (peak deviation, with HIDYN plus®)	≥ 112 dBA eff. / ≥ 100 dB CCIR peak
Limiter threshold	≤ 1 µV
Intermodulation attenuation	≥ 76 dB
Rejection of adjacent channels	≥ 66 dB
Suppression of spurious and harmonics	≥ 100 dB
Blocking	≥ 85 dB
Image rejection	≥ 100 dB
Spurious emissions (RF)	≤ - 80 dBm at HF input

D.2 SHURE Receiver / Transmitter Specifications

SHURE UHF WIRELESS SYSTEM — Specification Sheet

OVERALL SYSTEM

RF Carrier Frequency Range
782.125 to 809.875 MHz (782.125 to 805.875 MHz in the U.S.A.)

Effective Operating Range
152.5 m (500 ft.) under typical conditions, 1600 ft. line of sight

Frequency Response
50 to 15,000 Hz, ±2 dB

Total Harmonic Distortion
0.3% typical at 45 kHz deviation, 1 kHz modulation

Operating Temperature Range
–20° to 50° C (–4° to 122° F)

Dynamic Range
>102 dB, A–weighted

System Polarity
Positive voltage at transmitter input produces positive voltage at receiver audio outputs (tip or pin 2 relative to pin 3)

U1/U1L BODY–PACK TRANSMITTER

Output Power
10 mW

Audio Gain Adjustment Range
0–40 dB

Input Impedance
Tini Q.G. Connector: 18 kΩ, pin 4 wired to pin 3 for WL93 or other condenser microphone; 1 MΩ pin 4 open for dynamic microphone or instrument pickup. **NOTE:** Input impedance data for LEMO connector units available upon request.

Maximum Input Level
6 Vp–p (+7 dBV) for 1% THD, minimum gain setting, 1 kHz signal

Modulation
FM ±45 kHz deviation

Antenna
1/4 wave, whip antenna, 50Ω

Power Requirements
Two AA 1.5V alkaline batteries (Duracell MN1500)

Battery Life
12 hours typical (with Duracell MN1500 AA alkaline)

Dimensions
92.2 mm L x 64.7 mm W x 24.2 mm D (3 $^{29}/_{32}$ in. H x 2 $^{35}/_{64}$ in. W x $^{61}/_{64}$ in. D)

Weight
175.2 g (6.18 oz.) without battery

Certification
Type Accepted under FCC Parts 74; Certified by IC in Canada under TRC-78

U2 HAND–HELD TRANSMITTER

Output Power
10 mW

Audio Gain Adjustment Range
0 to 26 dB

Modulation
FM ±45 kHz deviation

Maximum Input Level
6 Vp–p (+7 dBV) for 1% THD, minimum gain setting, 1 kHz signal

Antenna
1/4 wave, helical, 50Ω,

Power Requirements
Two 1.5V AA alkaline batteries (Duracell MN1500)

Battery Life
12 hours typical (with Duracell MN1500 AA alkaline)

Dimensions
U2/58: 254 mm L x 50.8 mm Dia. (10 in. L x 2 in. Dia.)
U2/BETA 58: 254 mm L x 53.2 mm Dia. (10 in. L x 2 $^{3}/_{32}$ in. Dia.)
U2/87: 228.6 mm x 49.2 mm Dia. (9 in. L x 1 $^{15}/_{16}$ in. Dia.)
U2/BETA 87: 216 mm L x 50.8 mm Dia. (9 in. L x 2 in. Dia.)

Weight
U2/58, U2/BETA 58: 375.6 g (13.25 oz.) without battery
U2/87, U2/BETA 87: 303.1 g (10.69 oz.) without battery

Certification
Type Accepted under FCC Parts 74; Certified by IC in Canada under TRC-78

U4S/D MARCAD® DIVERSITY RECEIVER

RF Sensitivity
0.45 µV for 12 dB SINAD (typical)

Image Rejection
>90 dB

Spurious Rejection
>75 dB typical

Ultimate Quieting (ref. ±45 kHz deviation)
>100 dB, A–weighted

Squelch Quieting (ref. ±45 kHz deviation)
>95 dB, A–weighted

Antenna Input Impedance
50Ω nominal

Antenna
1/2 wave, dipole, 50Ω

Output Configuration
1/4 inch connector, balanced, 1 kΩ impedance
XLR connector, balanced, 30 Ω impedance

Mic/LineAudio Output
–22 dBV (mic) +2 dBV (line)

Power Requirements
90 to 230 VAC (automatic switching)

Dimensions
U4S/U4D: 44.5 mm H x 482.6 mm W x 295.3 mm D (1 $^{3}/_{4}$ H in. x 19 in. W x 11 $^{5}/_{8}$ D in.)

Weight
U4S: 3.30 kg (7 lb, 4.3 oz.)
U4D: 3.85 kg (8 lb, 0.5 oz.)

Certification
Approved under the Notification provision of FCC Part 15; Certified by IC in Canada under TRC-78

D.3 Trantec S-D7802 Receiver Specification

S-D7802 Dual Channel Receiver

Frequency Response:	20 Hz – 15 kHz
Audio Connector:	XLR ~ Analog, balanced 1/4" phone jack ~ Analog, unbalanced
Maximum Output Level:	Balanced XLR 20 dBu or more (line level) –20 dBu or more (microphone level) Unbalanced 1/4" phone jack 14 dBu or more (line level) –26 dBu or more (microphone level)
Dynamic Range:	100 dB or more
Distortion:	Less than 0.05%
Audio Mixing Input/Output:	1/4" phone jack
Headphone Output:	1/4" phone jack
D/A Converter Resolution:	24 bits, 48 kHz
Digital Audio Compression:	ADPCM
AES/EBU Output:	Balanced XLR
Word Clock Input for AES/EBU:	BNC input (75 Ω /open)
ID Number:	10 selectable numbers
LAN Port:	Ethernet including audio streaming
RF Frequency Range:	690–750 MHz or 790–870 MHz
RF Input:	2 BNC sockets (diversity), 50 Ω (actual)
RF Cascade Output:	–3dB, 2 BNC sockets (diversity), 50 Ω (actual)
Selectable Frequencies:	5 groups/16 channels per group in 30 MHz bandwidth, tunable in 25 kHz units and 2 selectable bands
Occupied Bandwidth:	200 kHz or less
Modulation System:	pai/4-DQPSK
Sensitivity (Error Free):	–90 dBm or less
Adjacent Channel Rejection:	50 dB or more
Image Rejection:	65 dB or more
Power Source:	100–230 VAC, 50/60 Hz, 400 mA
Operating Temperature Range:	–10 °C to +40 °C
Dimensions:	482 x 44 x 362.6 mm (1U)
Weight :	4 kg

D.4 Trantec S-D7300 Transmitter Specification

Model:	Handheld type: S-D7200 and S-D7210 Belt-pack type: S-D7300
Radio Signal Type:	G1D and G2D
Transmitting Frequency Range:	692.125 MHz – 720.975MHz (Band 1) 721.125MHz – 750.975MHz (Band 2)
Oscillation System:	Crystal-controlled PLL synthesizer system
Rated Antenna Power (W):	less than 50mW
Transmission Range:	Over 100M (open area)
Maximum Input Sound Pressure:	142dB spl (when gain is –15dB) (handheld type)
Maximum Input Level:	+7dBu (when gain is –27dB) (belt-pack type)
Internal Microphone Element:	S-D7200: Unidirectional moving-coil dynamic type S-D7210: Unidirectional electret condenser type
Audio LPF characteristics. (-3dB):	S-D7200/S-D7210: 50Hz S-D7300: 20Hz (MIC position), 30Hz (INST. Position)
Antenna (Built-in Type):	S-D7200/S-D7210: Internal helical antenna S-D7300: 1/4 whip antenna
Battery:	Two AA alkaline batteries
Battery Life:	Approx. 5.5 hr (typical)
Operating Temperature Range:	0 to 50°C
Modulation System:	pi/4 shift DQPSK
Audio Resolution:	24 bits
Encoding System:	Trantec Proprietary
Dynamic Range:	Over 103dB (A-weighted)
Distortion:	< 0.06%
Connector:	LEMO 3-pin connector (S-D7300 only)
Weight:	S-D7200 356 g (including batteries) S-D7210 312 g S-D7300 166 g
Dimensions:	S-D7200 / S-D7210 approx. 257 x 48mm S-D7300 approx. 93 x 62 x 20mm

D.5 Zaxcom RX4900 Receiver Specification

RX4900 Specifications

Receiver (x 4)

Receiver Type	True diversity single conversion digital demodulator
RF Modulation	Proprietary digital method
RF Frequency Range	518.0 to 872.0 MHz (blocks are 20 to 36 MHz)
RF Frequency Step	100 KHz
RF Bandwidth	**US Setting:** 200 KHz **Euro Setting:** 125 KHz
Channel Separation	500 KHz (700 KHz recommended)
Sensitivity	-110 dBm
Antenna Connector	50-ohn BNC female

Receiver Audio

Dynamic Range	114 dB
Distortion	0.001%
DAC Bit-depth	24 bit
DAC Rate	48 kHz
Audio Output Connector	8 – XLR-3M (mono)
Audio Output Level	**Mic:** -40 dBm **Line:** -6 dBm

Physical

Weight	4.2 lbs (1.9 kg)
Dimensions (H x W x D)	1.75" x 19" x 7.94" (44 mm x 483 mm x 202 mm)
External Power	9 to 18 VDC @ 800 mA
Internal Power	N/A
Display	Graphic LCD panel

D.6 Zaxcom TRX900 Transmitter Specification

Transmitter

RF Power Output	10 / 25 / 50 mW – Software selectable	
RF Modulation	Proprietary digital method	
RF Frequency Range	518.0 to 872.0 MHz (blocks are 20 to 36 MHz)	
RF Frequency Step	100 KHz	
RF Bandwidth	**US Setting:**	200 KHz
	Euro Setting:	125 KHz
Channel Separation	500 KHz (700 KHz recommended)	
Antenna Connector	50-ohm SSMA female	
Emission Designator	180 KV2E	
FCC Part	74.861	

Transmitter Audio

Dynamic Range	106 dB	
Distortion	0.001%	
Frequency Response	**Mode 0:**	20 Hz to 16 kHz
	T&M Model:	0.2 Hz to 16 kHz
Highpass Filter	'OFF' or 30 to 220 Hz, step: 10 (6 dB per octave)	
System Group Delay	**US Mono mode:**	3.6 ms
	Euro mode:	6 ms
	Stereo mode:	6 ms
Mic Power	3.3 VDC	
Mic Connector	3-pin micro-LEMO	
Input Range	–60 to –30 dBu	
Impedance	4.7 k ohms	
ADC Bit-depth	24 bits	
ADC Sampling-rate	48 kHz	

Timecode Reader/Generator

Clock Accuracy	1.54 PPM (1 frame out in 6 hours)
Timecode Type	SMPTE
Timecode Frame-rates	23.98, 24, 25, 29.97NDF, 29.97DF, 30NDF, 30DF