European Radiocommunications Committee (ERC)
within the European Conference of Postal and Telecommunications Administrations (CEPT)

HANDBOOK ON RADIO EQUIPMENT AND SYSTEMS
RADIO MICROPHONES AND SIMPLE WIDE BAND AUDIO LINKS

Rome, October 1996

CONTENTS

FOREWORD

This document is one in a series of three handbooks, which contain relevant information on the operation and specifications of radio equipment used by broadcasters and independent programme makers for SAB /SAP work.

The other parts in the series are:

- Video Links for ENG/OB use (ERC Report 38)
- Talkback (in production)

1. INTRODUCTION

The term SAB covers the use of radio by established terrestrial broadcasters in the making of their programmes.

The term SAP has been introduced to cover the radio use of independent programme makers and other commercial non broadcast use of radio as follows:

Services Ancillary to Programme making (SAP) support the activities carried out in the making of “programmes”. Programmes include film making, advertisements, corporate videos, sporting events, concerts, theatre and similar activities not initially meant for broadcasting to the general public.

The terms ENG and OB in this handbook have the current agreed definitions (CCIR report 803-2, Annex to Vol. X and XI, parts 3) which refer to video and not audio. To clarify the terms for audio extra information is provided.

The radio microphones and audio links referred to in this document are regarded as being for professional use. They will be licensed and operate within regulated spectrum.

2. DEFINITIONS

Radio microphones	Radio microphones (also referred to as wireless microphones or cordless microphones) are small, low power (<50 mW) transmitters designed to be worn on the body or handheld, for the transmission of close, personal sound. The receivers are more tailored to specific uses and may range from small and portable to rack mounted modules, as part of a multichannel system.
Simple wideband audio links	Simple wideband audio links are larger, higher power (>50 mW) transmitters, designed to be carried over the shoulder or operated from a fixed position to a distant receiver. The link can carry programme material in either mono or stereo, but a simple audio link will not normally be multiplexed.
ENG	Electronic News Gathering is the collection of television news stories without the use of film, using small handheld, electronic, colour cameras with microwave links to the news room and/or portable video tape recorders. These cameras are now often combined with a built in recorder for sound and video, using a single operator, but may use an on board microwave link for live events, or to a separate video recorder. Programme sound from the radio microphone(s) may be fed direct to the camera or to a sound recordist and separate recorder.
OB	Outside Broadcast is the temporary provision of programme making facilities at the location of on-going news, sport or other events, lasting from a few hours to several weeks. Outside Broadcasts are generally planned in advance, but it is often necessary to accommodate short notice changes of venue or unforeseen requirements. Video links are required for mobile links, portable links and cordless cameras at the OB location. Additionally, video links may be required as part of a temporary point to point connection between the OB van and the studio.

Programme sound is not normally recorded directly on a video camera/recorder. Both radio microphones and audio links are required depending on the size of the location and degree of public access. Additional audio links may be required as part of a temporary connection to the OB van depending on site conditions.

The definitions of ENG and OB are not mutually exclusive, certain operations could be in either category, even with ENG operation being part of a larger OB. For this document the term ENG is used to refer to small lightweight radio microphone systems operating to the video camera or mobile sound recordist. OB is used to refer to more complex radio systems with multiple radio microphones and where necessary, audio links.

Companding — A composite word from compressing and expanding. An analogue technique for improving the signal to noise ratio of a transmission system. The audio dynamic range is compressed before transmission, by increasing the low level signals, usually using a 2:1 logarithmic law (60 dB dynamic range reduced to 30 dB). The complementary process of expansion is carried out on the demodulated signal in the receiver.

Compander — The complementary circuitry in transmitter and receiver to implement the companding.

Contribution quality — A full broadcast quality signal used in the creation of a programme, the first RF link prior to any processing taking place.

Diversity reception — The use of two or more antennas with switching or combining receiver circuitry. The antennas are positioned to provide complementary coverage, dramatically reducing signal dropout due to multi-path cancellation.

Multichannel set — A number of frequencies which are selected to be intermodulation free for simultaneous use at one site.

Interleaved set — Other Multichannel sets within the same frequency band that can be used simultaneously when sufficient physical separation is available e.g., in an adjoining studio or theatre.

3. TYPE TESTING STANDARDS AND CURRENT FREQUENCY ALLOCATIONS

The majority of European countries have had type approval standards appropriate to radio microphones. All were based on a bandwidth of approximately 200 kHz and frequency modulation. CEPT Recommendation T/R 20-06 (1977) “Transmitters and Receivers for low power Cordless Microphones” was the first pan-European proposal and became the basis for many national type approval standards. However higher power audio link equipment largely was not covered by existing standards.

During 1991, ETSI was requested to update T/R 20-06 and this work has resulted in three standards :

1. I-ETS 300 422 Radio Equipment and Systems (RES);
Technical characteristics and test methods for radio
microphones in the 25 MHz to 3 GHz frequency range

2. ETS 300 454 Radio Equipment and Systems (RES);
Wide band audio links; Technical characteristics and test methods

1. ETS 300 445 Radio Equipment and Systems (RES);
Electro-Magnetic Compatibility (EMC) standard for radio microphones
and similar Radio Frequency (RF) audio link equipment

Within the ETSI standards a radio microphone is a device of 50 mWatts e.r.p. or less and similar devices above this power limit are referred to as audio links.

Radio microphones and audio links can both be considered as an alternative when the physical connection of a cable is impractical or undesirable. In order to replace the cable, the radio system must be capable of providing a full audio bandwidth signal (20 Hz - 20 kHz), with high dynamic range and good signal to noise performance even under weak signal conditions.

To achieve these operational criteria, to date, both radio microphones and audio links have used wide band frequency modulation.

As part of the updating of T/R 20-06, ETSI carried out a survey of frequency allocations for Radio Microphones within Europe. The results can be found in Appendix A. When examining the apparently large allocations in some countries, it should be borne in mind that allocations are often on a geographically restricted basis dependent upon allocations to other users of the band.

In many countries allocations are to be found in the 30 - 50 MHz range. Because of man made interference and length of aerial, the band is rarely used for high quality radio microphones.

4. TYPICAL APPLICATIONS

With the advent of the lightweight combined video camera/recorder, an ENG crew can comprise only a reporter and a camera operator. To enable reports to be recorded in difficult locations, a radio microphone is used between the reporter and the camera.

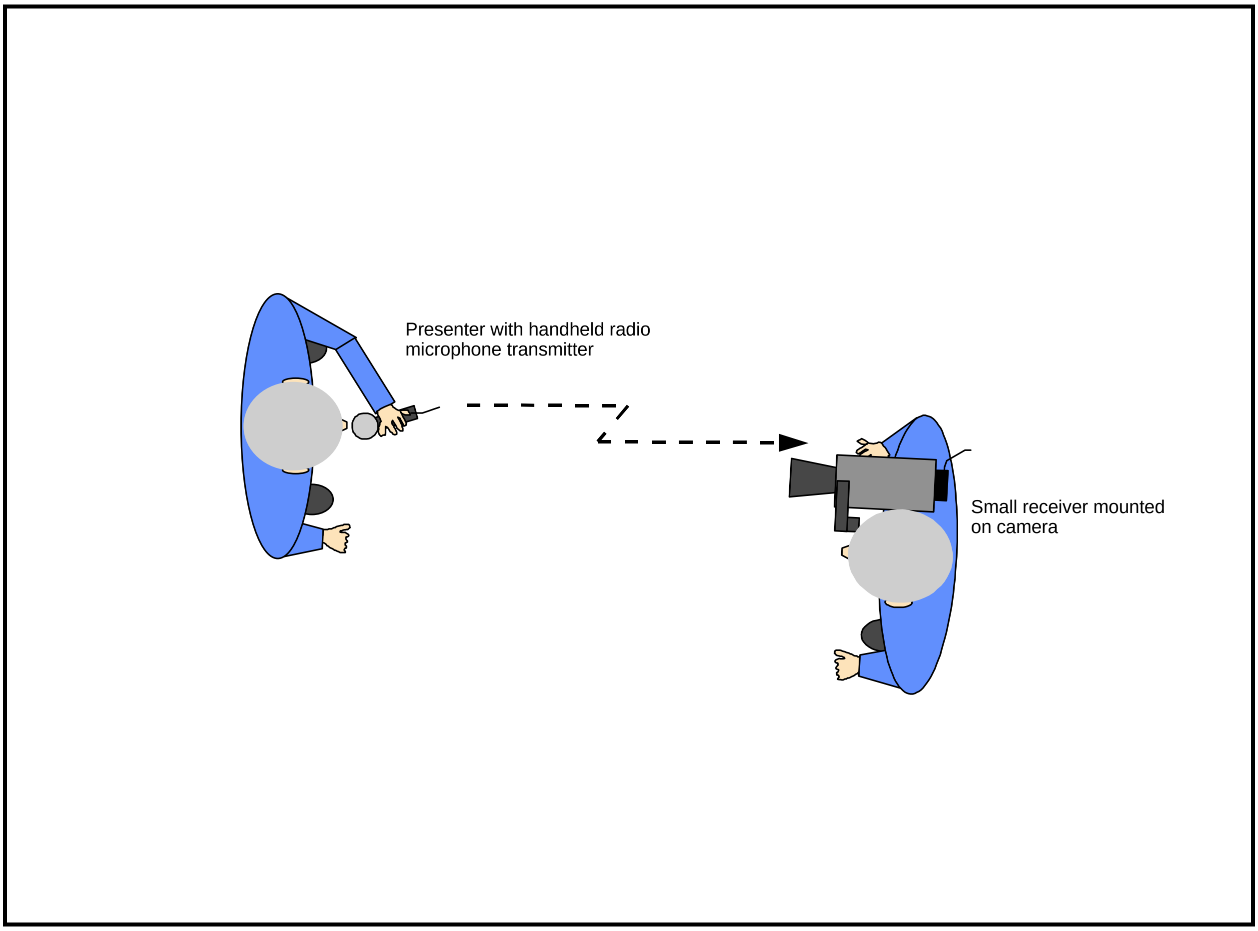


Figure 1: Reporter to camera (handheld transmitter, small camera mounted receiver)

When news interviews have to be made quickly a handheld radio microphone transmitter is used, with the interviewer wearing a body worn transmitter and a small lapel microphone.

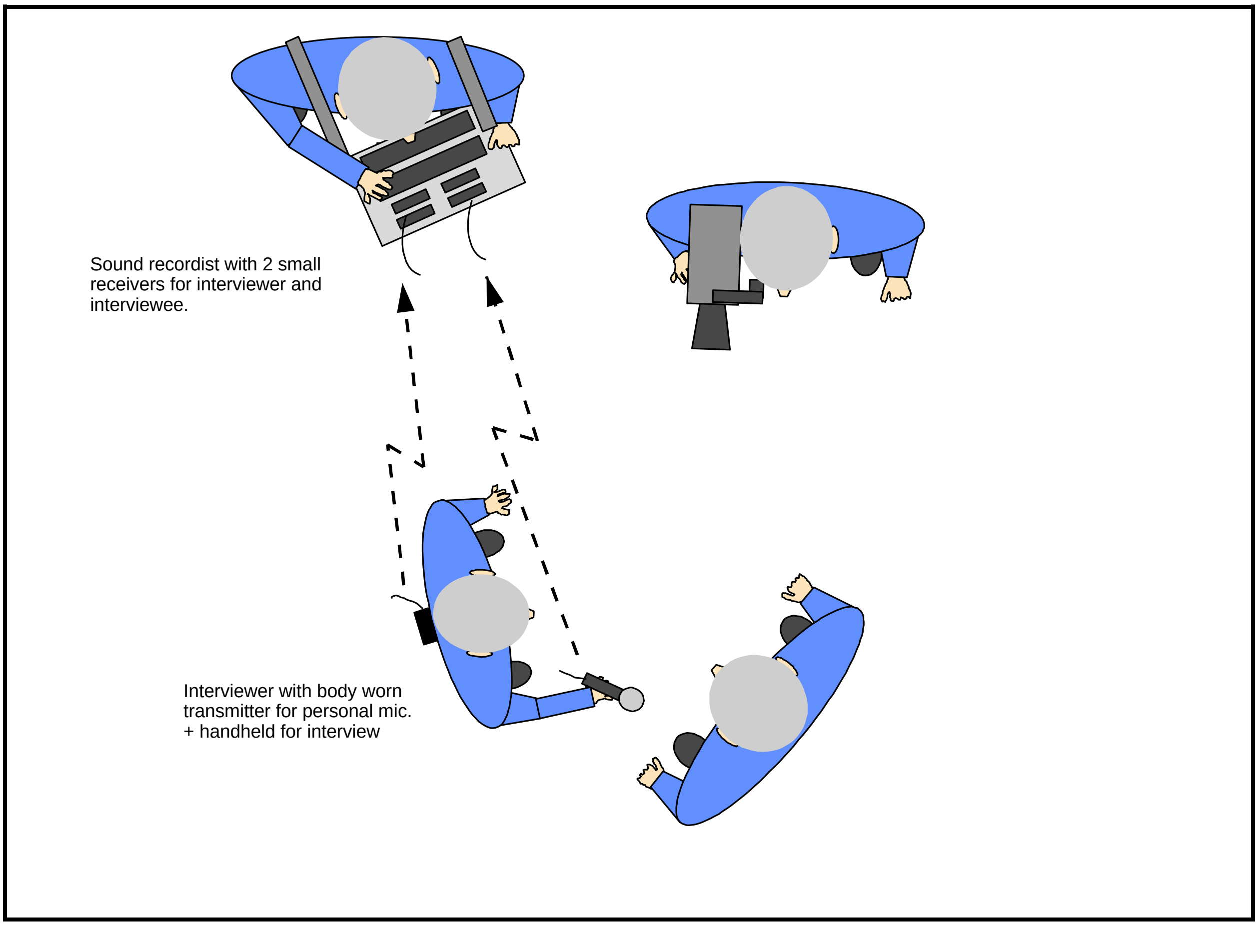


Figure 2: Interviewer + interviewee to sound recordist (1 handheld, 1 body worn transmitter, 2 small receivers)

For documentary type productions a sound operator will mix the sound from a number of radio microphones, either for recording as separate audio, or to be recorded on the video recorder. It is common practice to use a radio microphone as a link from the mixer to the recorder to ease freedom of movement.

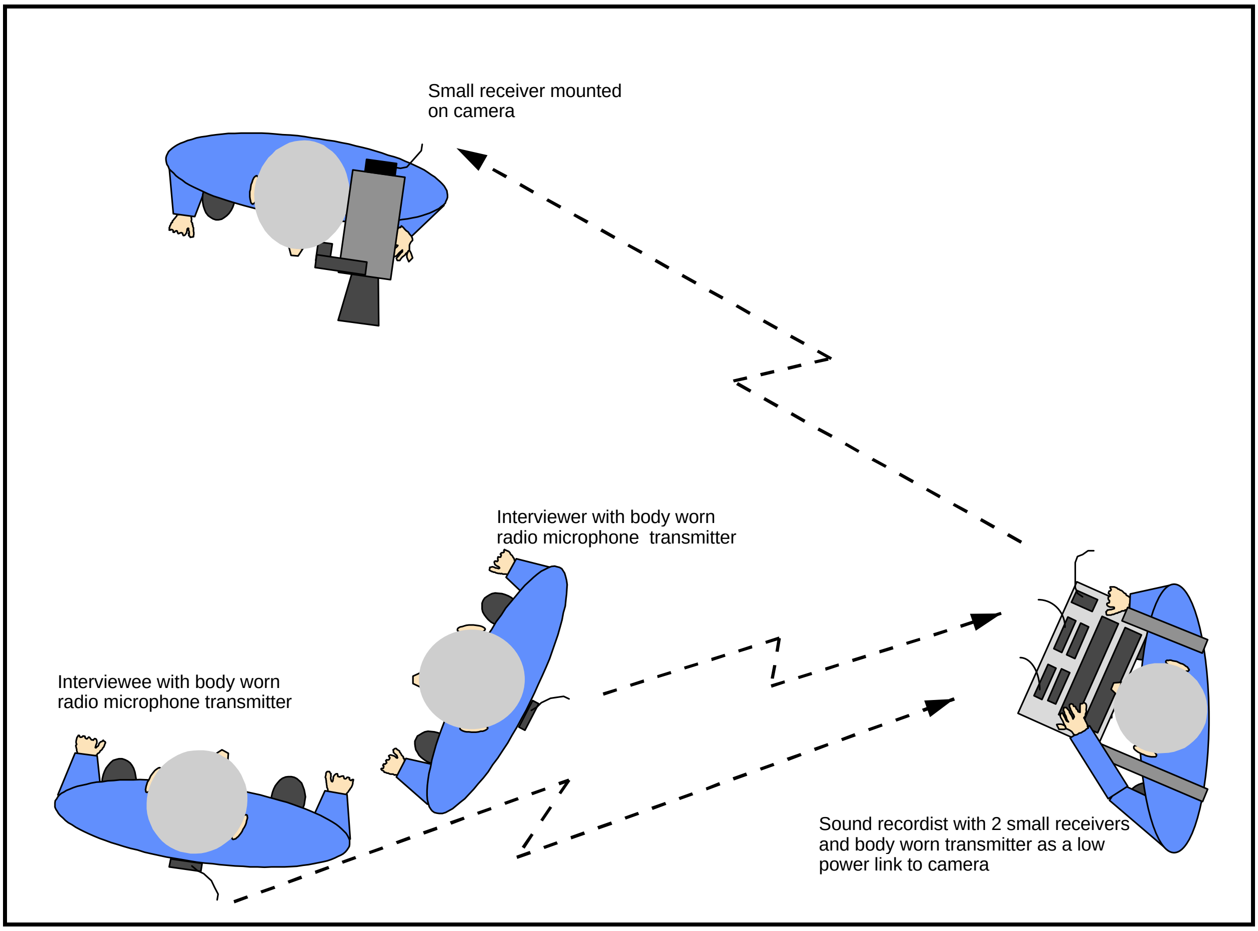


Figure 3: Interviewer + interviewee to sound recordist, link between sound recordist and camera. (3 body pack transmitters, 3 small receivers)

For outside broadcast applications the division between radio microphones (<50 mW) and audio links (>50 mW) is largely academic. For instance, at an outside broadcast event such as a golf tournament, the audio may need to be transmitted over a distance of 1 - 2 Km in order to get the signals from the playing area back to the outside broadcast vehicle. In this situation the device would need to be between 1 and 5 watts, depending on local factors. If the transmitter is a conventional 10 mW handheld radio microphone, held by an interviewer, it may feed into an adjacent audio link system worn by an assistant which then relays the signal to the outside broadcast unit.

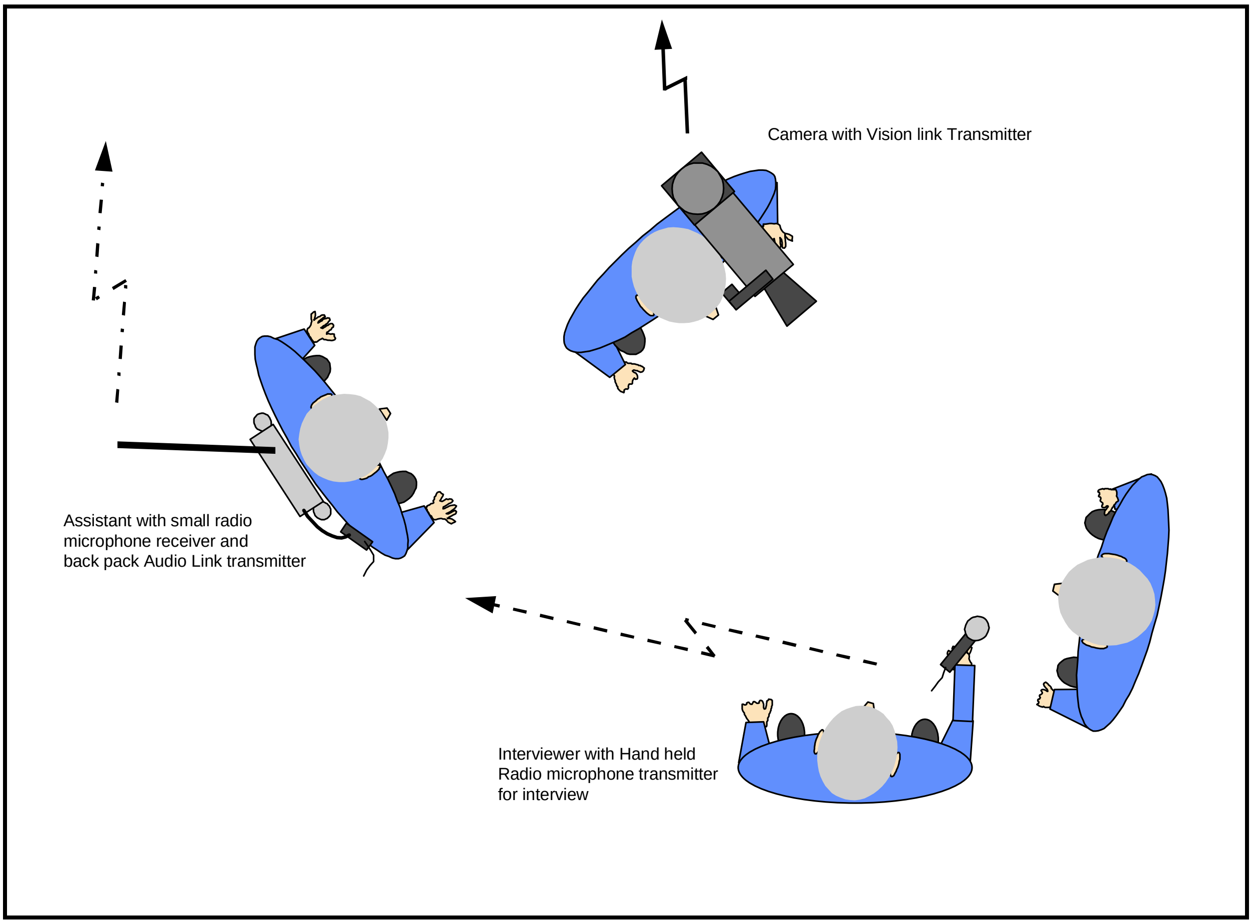


Figure 4: Interviewer to assistant, link to OB van (1 handheld transmitter, 1 small receiver, 1 link transmitter)

Alternatively it could be a conventional body worn radio microphone worn by the interviewer with an attached booster amplifier giving a higher final output power direct without the use of an additional audio link. However, power will be limited by size/battery considerations and not normally be above 500 mW.

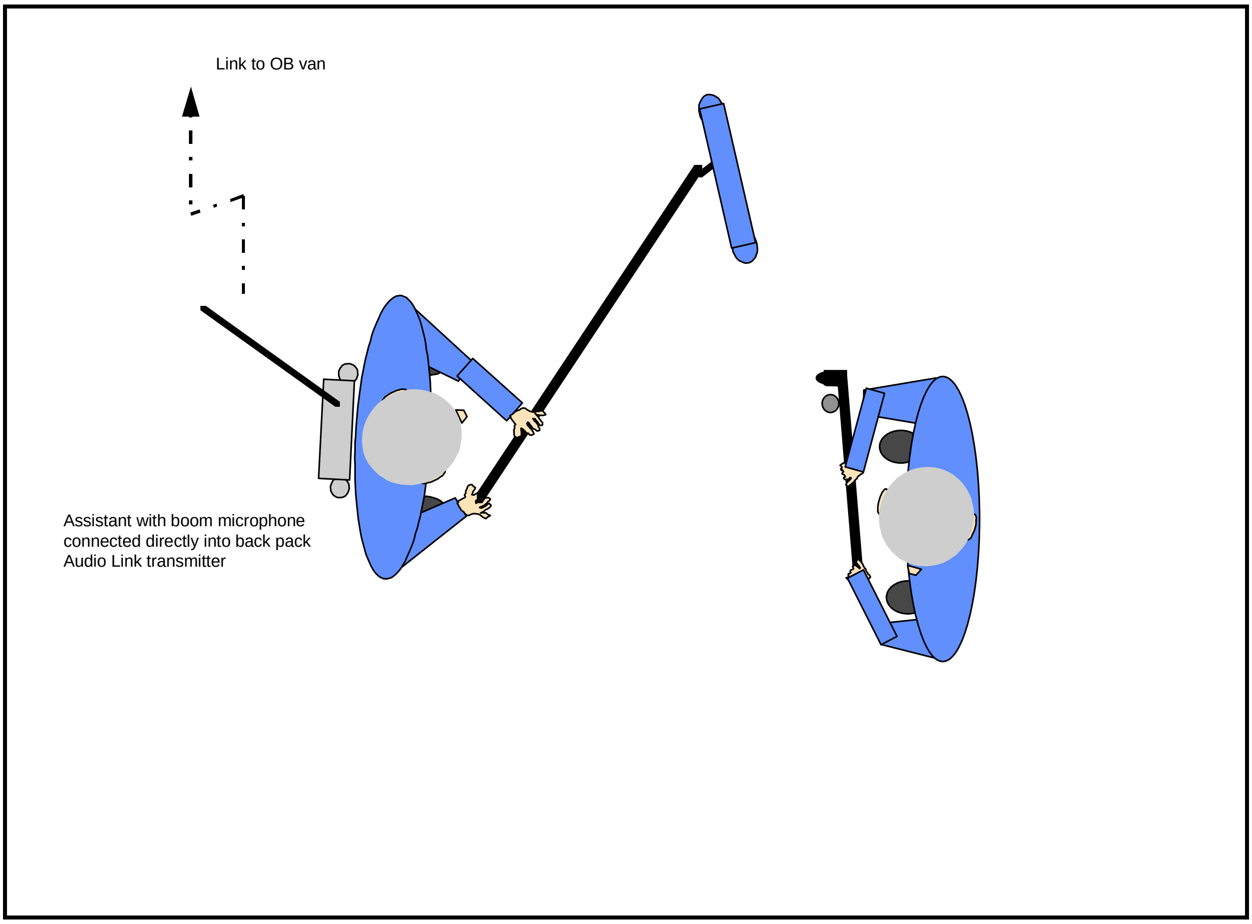


Figure 5: Location sound (Direct feed from microphone to link transmitter carried by a sound assistant as a backpack)

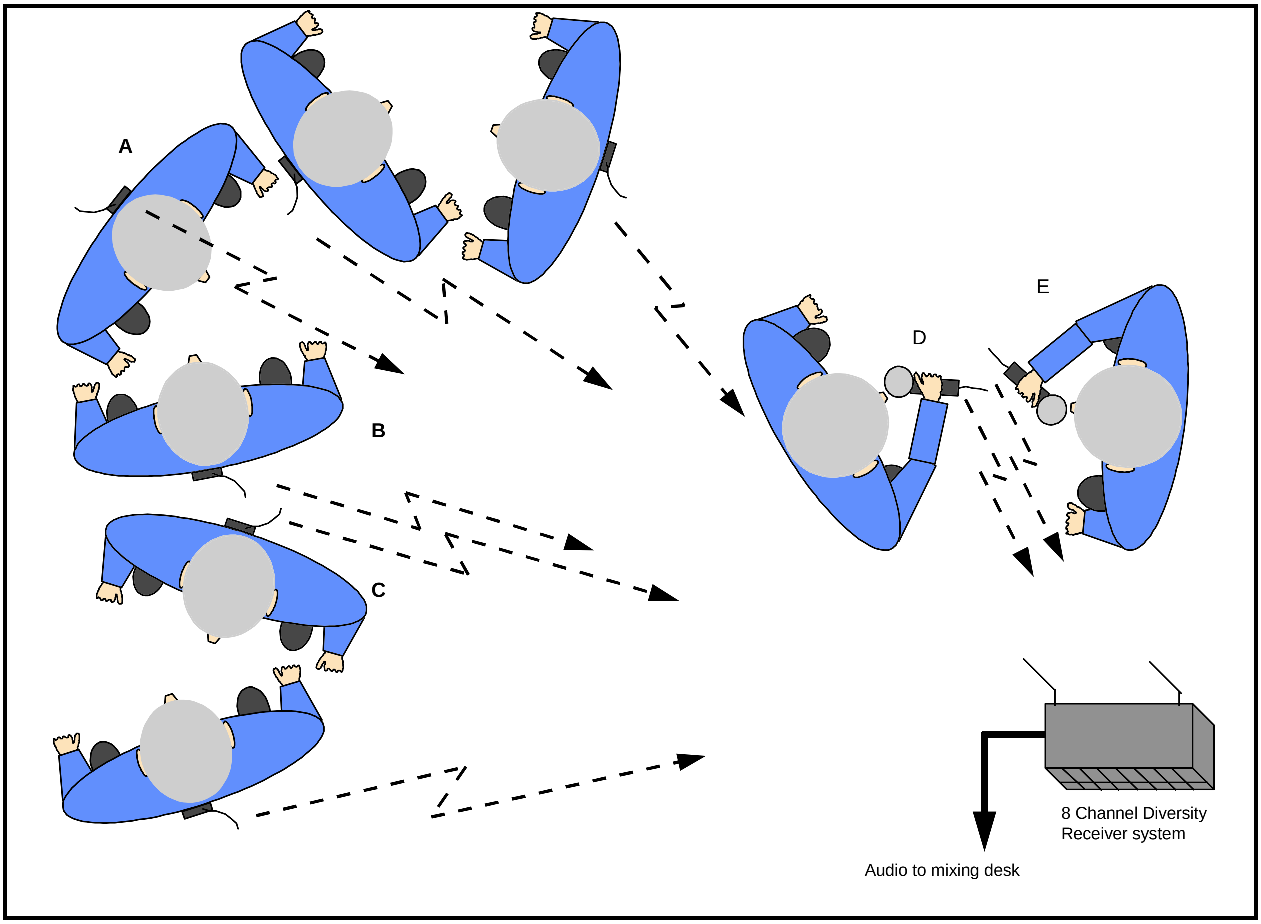


Figure 6: Musical theatrical or studio production

Performers to multichannel receiving system, then audio to a mixer (6 body-pack radio microphone transmitters, 2 handheld radio microphone transmitters, 8 channel diversity receiving system)

key:

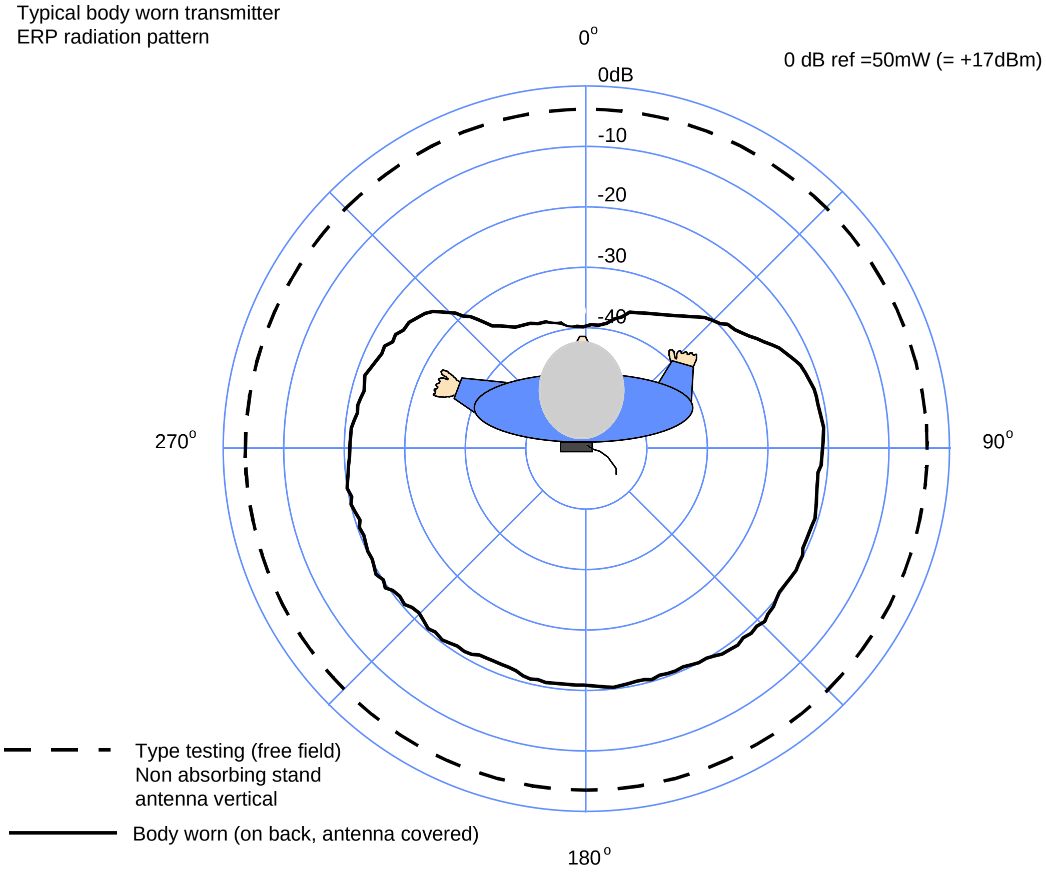
A Minimum transmitted e.r.p. in direction of receive antenna

B & C Close spacing of transmitters produce 3rd order intermodulation products

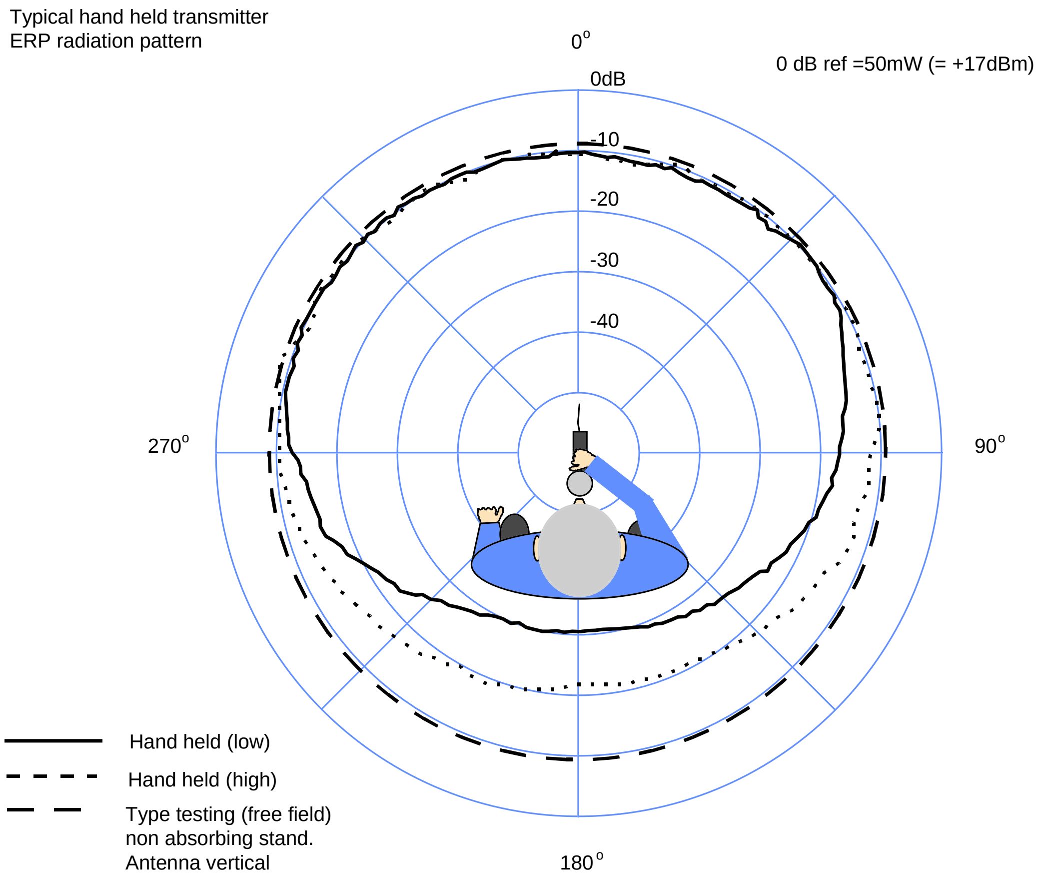
D & E Close spacing of handheld transmitters produce 3rd order intermodulation products. Their higher e.r.p. close to the receiving system may also provoke blocking of the weaker signals.

5. RADIATED POWER POLAR PATTERNS FOR BODY WORN AND HANDHELD TRANSMITTERS

650 MHz



650 MHz


Typical hand held transmitter
ERP radiation pattern
0°
0 dB ref =50mW (= +17dBm)
0dB
-10
-20
-30
-40
270°
90°
180°
Hand held (low)
Hand held (high)
Type testing (free field)
non absorbing stand.
Antenna vertical

6. RADIO MICROPHONE TECHNICAL PARAMETERS

In its simplest form a radio microphone consists of one transmitter and one receiver, and for this configuration the design parameters are only those to meet type approval. As the number of channels in simultaneous use at one site increases, consideration of parameters such as intermodulation products, intermodulation attenuation, RF protection ratio, propagation and proximity of other systems are vital. Unlike private mobile radios or other “communication” quality systems, the slightest interference or disturbance of the signal is critical and, in the majority of cases, amplified via the powerful public address or theatre systems to the distress of audience and performers alike or broadcast to many millions of radio or television receivers.

The level of interference protection specified for multichannel sets varies between manufacturers. It may also be varied by a manufacturer to tailor a set to a specific requirement. However, manufacturers of professional systems will avoid at least the 3rd order intermodulation products occurring exactly on the frequency of another transmitter within a set (0 offset) (Appendix C).

The frequency offset from the wanted carriers of the intermodulation interference is equal to multiples of any grid spacing (Appendix E).

For example: With a grid spacing of 25 kHz the offset of the intermodulation products can only be: 0,25,50,75,100........kHz.

As a corollary, if the minimum allowable intermodulation offset is 25 kHz then a grid spacing of 25 kHz is required.

In frequency planning for a multichannel radio microphone set, the receiver RF protection ratio is of great importance (Appendix F).

To maximise the number of radio microphone channels that can be operated simultaneously within a given bandwidth, the interfering intermodulation signals have to be allowed to fall within the bandwidth of the wanted receiver. If a sufficiently fine grid is used, the maximum use can be made of the available spectrum.

After allowing a suitable practical protection ratio between wanted signal strength and interfering signal strength a minimum frequency difference between the two can be derived. This is calculated to maintain a suitable RF protection ratio under projected operating conditions. This frequency difference may vary depending upon the relative strengths and the mechanism involved in producing the interfering intermodulation products.

High quality equipment may also use techniques such as companding, which enables a lower RF protection ratio to be used within a multichannel set while still maintaining the required audio signal/noise ratio at the receiver output. In less demanding applications which do not require extremes of operating range or audio dynamic range, the use of companding may allow the use of narrower bandwidths. The former simple choice of type approval standards between wide band (200 kHz, high quality) and narrow band (15 kHz, speech quality) did not encourage manufacturers to develop a high quality intermediate bandwidth system. The new ETSI standards, (I-ETS 300 422, ETS 300 454) now provide the framework for the development of these more spectrum efficient systems for both radio microphones and simple wideband audio links.

An example of current practice is described in a paper presented at the 1992 AES meeting in Vienna. Stefan Frese suggests a minimum intermodulation offset of 25 kHz and describes a 12 channel 200 kHz radio microphone set designed to fit in an 8 MHz band. This set assumes the use of companding to reduce the audible effects of the intermodulation interference on the wanted signal. Even with the allowed high level of intermodulation interference this set is still only using 12 x 200 kHz = 2.4 MHz of the 8 MHz band, i.e. 30 %. Assuming a separation between users, the remaining 70 % of the band can be used for further interleaving sets which can significantly improve the band utilisation.

As the number of transmitters operating simultaneously increases, the number of intermodulation products increase at a greater rate. For a single multichannel set, the more channels that need to operate simultaneously, the less efficient is the use of spectrum. This is true if only one set of frequencies is allowed in a band, the interleaving of two or more multichannel sets will greatly improve the efficient use of the spectrum (Appendix C).

Although a sufficient ratio of wanted to unwanted signal strength needs to be assured for all operating conditions (typically 30 - 40 dB), any unnecessary increase in transmitter power will be counter productive.

1. Increasing all transmitter power by 10 dB produces a 30 dB increase in receiver generated 3rd order intermodulation levels.

2. As the number of radio microphone channels increases, multichannel receiver RF input circuits have to handle relatively high power levels, even from a set of low power transmitters (<50 mW).

From 1 and 2 above, it is important that the sum of the power levels of wanted signals at the receiver input does not cause high levels of intermodulation to be produced in the receiver. With carefully balanced power levels, more frequency efficient multichannel radio microphone sets can be produced.

It can be seen that the efficient utilisation of spectrum for radio microphone use is affected by:

- Grid spacing
- Channel planning
- Output power
- Channel bandwidth

7. RADIO MICROPHONE SYSTEM CALCULATIONS

Radio microphones have a wide variety of uses in SAB and SAP applications.

Two examples are chosen to calculate system performance, using 50 mW (bodyworn) and 10 mW (handheld) transmitter types.

a) Outside drama or documentary

a small number of radio microphone transmitters, but maximum range required. Transmitters body worn under clothing.

In this case the noise floor will be the limiting factor.

The maximum operating range for a noise limited system is calculated below :

	Parameter	VHF	UHF
(1)	Thermal Noise (KTB)	-123 dBm	-123 dBm
(2)	Mobile Receiver noise figure (F)	3 dB	4 dB
(3)	Receiver noise floor (1) + (2)	-120 dBm	-119 dBm
(4)	Interference allowance (note 1)	10 dB	0 dB
(5)	Receiver noise + interference (3) + (4)	-110 dBm	-119 dBm
(6)	Minimum signal to noise (note 2)	30 dB	30 dB
(7)	Minimum carrier to noise (note 2)	20 dB	20 dB
(8)	Rx antenna gain	0 dBi	0 dBi
(9)	Minimum unable Rx signal (5) + (7) + (8)	-90 dBm	-99 dBm
(10)	Minimum fade/multipath margin	30 dB	30 dB
(11)	Required unfaded Rx signal level (9) + (10)	-60 dBm	-69 dBm
(12)	Transmitter free field ERP	+15 dBm	+14 dBm
(13)	Tx Antenna efficiency (close to body)	-15 dB	-15 dB
(14)	Body shielding	-18 dB	-22 dB
(15)	Minimum Transmitter E.I.R.P. (12) + (13) + (14)	-18 dBm	-23 dBm
	Free field range allowance (15) - (11)	**42 dB**	**46 dB**

Note:

1. Urban (man made) noise has in the past been largely a problem affecting frequencies <170 MHz. The introduction of fast computers and similar digital control equipment with high (legal) levels of spurious radiation has meant the ambient noise for frequencies between 170 MHz and 300 MHz has typically risen above the receiver noise floor by 10 dB. This problem will continue to affect ever higher frequencies unless the spurious radiation limits are improved.

2. For a system using companding circuitry, a minimum S/N ratio of 30 dB is required at the expander to prevent mistracking. Using FM modulation with 50 µS pre-emphasis, this approximately equates to an input carrier to noise of 20 dB.

From this calculated Free field range allowance, the maximum operating range can be calculated for different operating frequencies (see Appendix B).

Table 1

Maximum operating range of body worn radio microphones (noise limited)

Frequency (MHz)	**Range (m)**
200	15
300	10
400	12
500	10
600	8.5
700	7.5
800	6
900	5.5
1000	5

Note:

1. Above the effects of man made noise, doubling the frequency of operation halves the maximum operating range.

2. The use of diversity reception will allow the fade margin to be reduced to 20 dB, this gives a threefold increase in maximum operating range.

3. When circumstances allow, 6 dB antenna gain will double the range.

b) Theatre or studio production

Large numbers of transmitters body worn under clothing, often a number of handheld transmitters are used as well. Potentially a large number of intermodulation products, which are allowed to fall within used channels to maximise set size, with a possible small differential between wanted /unwanted signal strengths at the multichannel diversity receiver system antenna input .

The antenna placing is critical:

a) To reduce fade/multipath allowance.
b) To avoid body worn radiation minimum (body shielding)
c) To give greatest range of movement

Taking the scenario where two transmitters are close to an antenna, and the wanted transmitter is more distant, see Typical Applications, Figure 6.

In this case the wanted signal to intermodulation ratio can become the limiting factor for operating range.

Maximum operating range for an intermodulation limited system is calculated below :

	Parameter	VHF (200 MHz)	UHF (800 MHz)
(1)	Bodyworn (B/W) Transmitter free field ERP	+15 dBm	+14 dBm
(2)	Handheld (H/H) Transmitter free field ERP	+10 dBm	+10 dBm
(3)	B/W Tx Antenna efficiency (close to body)	-15 dB	-15 dB
(4)	H/H Tx antenna efficiency	-6 dB	-6 dB
(5)	Typical Tx 3rd order mixing loss	20 dB	20 dB
(6)	Minimum distance between transmitters	0.25 m	0.25 m
(7)	0.25m path loss (see appendix B)	6.4 dB	18.5 dB
(8)	2 tone B/W Tx generated IM level (1) + 3 • (3) - (5) - (7)	-56.4 dBm	-69.5 dBm
(9)	2 tone H/H Tx generated IM level (2) + 3 • (4) - (5) - (7)	-34.4 dBm	-46.5 dBm
(10)	Minimum distance between Tx and Rx antenna	3 m	3 m
(11)	3m path loss (see Appendix B)	28 dB	40 dB
(12)	B/W IM level at Rx antenna (8) - (11)	-84.5 dBm	-109.5 dBm
(13)	H/H IM level at Rx antenna (9) - (11)	-62.4 dBm	-86.5 dBm
(14)	IMa (see Note 1)	6 dB	6 dB
(15)	Protection ratio (see Note 2)	15 dB	15 dB

Note:

1. Intermodulation allowance (IMa) dB = 10 • log(n) where n = number of 3rd order transmitter generated intermodulation products falling within the bandwidth of a wanted channel. Typical number = 4 for a 12 channel set in 8 MHz. IMa = 6 dB

2. At 50 kHz offset for worst intermodulation spacing the protection ratio of a typical receiver gives 15 dB protection

Theatre or studio production continued.

	Parameter	**VHF (200 MHz)**	**UHF (800 MHz)**
(16)	Effective IM level/channel from B/W Tx (12) + (14) - (15)	-93.4 dBm	-118.5 dBm
(17)	Effective IM level/channel from H/H Tx (13) + (14) - (15)	-71.4 dBm	-95.5 dBm
(18)	Body shielding	-3 dB	-6 dB
(19)	B/W Transmitter E.I.R.P. (1) + (3) + (18)	-3 dBm	-7 dBm
(20)	H/H Transmitter E.I.R.P. (2) + (4) + (18)	+1 dBm	-2 dBm
(21)	Minimum fade/multipath margin	20 dB	20 dB
(22)	Minimum carrier to interference	20 dB	20 dB
(23)	Minimum wanted signal at Rx antenna. B/W IM (16) + (21) + (22)	-53.4 dBm	-78.5 dBm
(24)	Minimum wanted signal at Rx antenna. H/H IM (17) + (21) + (22)	-31.4 dBm	-55.5 dBm

Free field range allowances

1.	B/W Tx, B/W interferer (19) - (23)	50.4 dB	71.5 dB
2.	B/W Tx, H/H interferer (19) - (24)	28.4 dB	48.5 dB
3.	H/H Tx, B/W interferer (20) - (23)	54.4 dB	76.5 dB
4.	H/H Tx, H/H interferer (20) - (24)	32.4 dB	53.5 dB

Maximum range to antenna (From Appendix B)

Maximum Operating Range (Intermodulation limited)

1.		40 m	>50 m
2.	note 1	3 m	8 m
3.		>50 m	>50 m
4.	note 2	5 m	15 m

Note:

1. The worst case intermodulation scenario, 2 above, with close handheld interferers would be unworkable.

2. Case 4 above, not recommended.

8. RADIO MICROPHONE DEVELOPMENT

Radio Microphones have been in use since the early 1940's mainly in the film and broadcast industries. In the 1970's they started to appear in a broader area of the entertainment industry, especially within the theatres and concert halls. Since the 1980's the popularity of stage musicals has meant an explosion in the use of multichannel systems within theatres throughout Europe. The development of these large multi-channel systems has been reflected in both outside broadcast and studio use as programme makers either cover existing productions or produce their own. The indoor use of large multichannel sets of radio microphones now falls mainly into two categories:

1. The large single studio/stage multichannel set (can be >40 channels).

This requires a high level of intermodulation interference protection between the chosen radio microphone frequencies in the set as the transmitters will be operating in close proximity to each other.

2. The use of large numbers of radio microphones in adjacent halls or studios within a complex but usually with each hall or stage operating less channels than 1 above.

This situation requires a high level of intermodulation interference protection between the radio microphones within each set, but can have lower intermodulation protection between frequencies in other sets. This is where the interleaving of frequency sets will give considerable improvements in spectrum use (Appendix C).

In the London theatre an average of 26 radio microphone channels are in use with peaks to 40 and an expected rise up to 50 channels when some of the newer American musical productions arrive. Similar numbers of channels are also required for events where performers use an extensive radio infrastructure, including conventional multichannel radio microphone systems as well as the ever increasingly popular in-ear monitoring systems. These are, in effect, radio microphones operating in the reverse direction, i.e. a transmitter located backstage which is fed with the mixed audio output from the band etc. and transmitted to the performer who is then able to hear the mixed signal at a comfortable audio level, without the necessity of being in front of the speaker system.

9. DIGITAL POSSIBILITIES

The reasons stated for using digital modulation for transmitting an audio signal are to provide better spectrum efficiency and better transmission quality. For the foreseeable future these are mutually exclusive aims for radio microphones, in practice <u>either</u> higher quality <u>or</u> spectrum efficiency is achieved.

The radio microphone is part of the first link in the production chain, (microphone to radio microphone transmitter, to receiver, then to the mixer or recorder), i.e. a contribution link. As such it has to maintain the highest possible audio quality while constrained both by legal limits (bandwidth and power), and user demands (size, weight, battery life).

Typical system figures are as follows:

Peak S/N ratio	>100 dB
Frequency response	50 Hz - 18 kHz - 2 dB
Distortion	<0.2 %
Transmitter battery life (continuous use)	>6 hours

Current analogue radio microphone systems are capable of meeting these requirements, even under adverse conditions using analogue companding techniques in a RF channel bandwidth of less than 200 kHz (Appendix G).

Linear coding

To provide the required contribution quality of a wide bandwidth audio signal by means of a linearly coded digital system, the following parameters are required as a minimum:

44.1 kHz sample rate (for 18 kHz audio bandwidth)
18 bit sample accuracy (for 100 dB signal to noise)

This gives a raw bit rate of 793.8 kbits/sec.

Using GMSK (Gaussian Filtered Minimum Shift Keying) modulation, (0.3 Bt) with a bit rate of 793.8 kbits/sec. this gives :

-40 dB bandwidth	>1 MHz
Minimum channel spacing	600 kHz

Clearly, better spectrum efficiency is not simply attained by using digital modulation rather than analogue. A combination of digital processing for bit rate reduction (compression) and digital modulation is necessary.

Digital compression for high quality signals

The use of cascaded digital bit rate reduction in contribution circuits is a highly contentious issue since any reduction in signal quality once lost cannot be restored.

The minimum recommended bit rate for high quality audio is 192 kbit/sec., (ref. ITU-T, MPEG) thus a maximum of 4:1 compression ratio should be used, but even then the RF bandwidth (GMSK -40 dB) is still >280 kHz (<u>without</u> error correction). It must be noted that to achieve satisfactory overall performance through the production chain, the bit rate of individual links need to be significantly greater than the minimum value.

Two main compression techniques are currently employed for wideband signals, frequency domain (Transform Coding) and time domain (ADPCM).

Frequency domain coding

The frequency domain approach is capable of higher compression ratios, thus potentially reducing bandwidth, but has serious drawbacks for programme contribution signals.

The signal is split into a large number of audio sub-bands which are analysed by comparison with a standard auditory model. The relative audibility of the signal in each band determines how accurately it is coded, with the transmission stripped of ‘inaudible’ components. This means that audio companding cannot be used before the digital compression as serious mistracking can result from this loss of information. This coding takes a significant time (typically up to 250 ms). For systems, which have to operate in real time with a mix of transmitted and live sound, or live outside broadcasts, where lip synch is essential, this delay is unacceptable. For every pass through a psycho-acoustic coding algorithm, information is lost, while cascading different coding algorithms may add unwanted transient artefacts to the signal.

Time domain coding

For applications where coding delay is critical, time domain coding is potentially a more attractive approach.

Typically the signal is split into only 4 sub-bands by means of a digital filter. Each of these bands is coded by predictive analysis, the coder predicts what the next sample in the audio signal will be and subtracts this prediction from the actual sample. The resulting error signal is transmitted to the decoder which then adds back in the prediction from identical tables stored in the decoder. Time domain coding is faster, (<5 ms) and is suitable for live transmissions, but its most serious drawback for use in small lightweight equipment is the power consumption and complexity of the circuitry needed to implement this form of digital compressed signal. The operating time would be cut from more than 6 hours to less than 2 for existing sized small pocket transmitters.

Digital compression for communications quality speech

Speech compressors or codecs for this application are designed to reduce the signal to the absolute minimum necessary for intelligibility, not fidelity. Currently operating with compression ratios of between 8:1 and 12:1, >16:1 is a target for the 'half rate' codec. The high compression ratio is obtained by using a coding algorithm specifically for voice only. Human speech is generated by the vocal tract and only produces a limited range of audio sounds. The codec effectively recognises these basic speech sounds and translates them in an abbreviated form using a voice coding algorithm, allowing only the main characteristics of the speech waveform to be preserved. If non speech sounds, (loud ambient noises, music, etc.) are transmitted, the resulting signal is very distorted because it does not conform to the human speech model used by the codec.

Propagation considerations

Preceding sections have outlined operational parameters for a selection of Radio Microphone systems. It has been shown, in almost every example, that the necessary operating environment is not conducive to a good radio link being established. Operational constraints such as inefficient antennas (body absorption), reduced effective radiated power (body shielding) or interference from multiple radio microphones, can substantially reduce the operational range.

In a built up studio or theatre, containing large sections of scenery, elaborate lighting gantries, cameras and of course many personnel, another mechanism which may result in large signal fluctuations is multipath propagation. The resultant signal at the receiver, is a summation of the many contributions from direct and reflected paths. As the transmitter (performer) moves around, so the relative levels and phases of these contributions change. Sometimes, the addition of several contributions will be destructive and complete signal cancellation occurs at the receiver.

Usually, the location of the receiving antenna is adjusted to ensure that such a 'dropout' will not occur whilst the performers remain in the planned area, but sometimes this is not possible. If the performance is being recorded and if the resulting impairment is severe, there is of course the possibility of retaking the scene although live shows offer no such luxury. For this reason modern radio microphone systems are engineered to cope with 'dropout' gracefully, usually with the signal then being received in a different location by a different receiving antenna (diversity reception).

Under ideal conditions, current analogue transmission quality can match digital quality, but as the propagation conditions deteriorate the signal quality of the digital transmission remains constant while the analogue signal degrades. An audio signal which is digitally compressed and transmitted using advanced digital modulation will offer significant resistance to multipath propagation and so will provide advantages over the current analogue systems.

Currently, to implement such advanced technology will exceed the design limits of lightweight radio microphones for size, weight and power consumption. It is likely that any progress on digital radio microphones will be made using simple modulation systems. Unfortunately these carry the penalty of abrupt failure followed by a significant recovery time, which increases as the compression rate increases.

The addition of an error correction overhead allows satisfactory operation closer to the failure point, but inevitably gives an even more abrupt transition at the limit. Furthermore, this will increase the transmitted bit rate and hence the bandwidth of the system, but the presence of error correction will usually allow the digitally coded channels to operate with a lower protection ratio than equivalent analogue channels. There is clearly a conflict between, on one hand, high degrees of digital compression aimed at reducing the signal bandwidth and on the other hand, simple systems incorporating a controlled graceful failure.

9.1. Spread Spectrum

Spread spectrum is a term used to describe modulation systems that deliberately spread the signal over a much wider bandwidth than is required by conventional systems. Rather than allocating separate discrete frequencies to individual channels, a frequency band has to be made available.

Spread spectrum techniques may offer a possible solution to the bit rate/bandwidth compromise.

There are a variety of ways to spread the signal across the band, with fast frequency hopping and direct sequence spreading (CDMA, Code Division Multiple Access) the most used.

Frequency hopping

Frequency hopping systems simply change the operating frequency of the transmitter at intervals. The receiver has to follow the hopping transmission and continue to demodulate the changing carrier to recover the wanted signal.

Developed originally to provide better security of transmission for military communications systems, for radio microphones applications there is no real benefit in this technique.

Direct sequence

In direct sequence systems, a high frequency digital signal is multiplied with the wanted modulation to spread the base band (wanted) signal out over a wider bandwidth. Typically the spreading code is at least 10 times the data rate of the baseband signal and is an integral multiple of that rate. Different users use different spreading codes, consequently the spreading codes have to have the property that the signals they generate do not interfere with each other.

Many manufacturers and Broadcasting organisations have investigated the use of spreading techniques for both analogue and digital modulation. While the conclusion was that there is no net advantage in spreading an analogue signal over existing conventional FM, by using digital modulation the spreading technique may prove to be of benefit to radio microphone systems once the practical constraints have been overcome.

9.2. Conclusion

The main obstacles to the successful implementation of digital modulation in lightweight radio microphone transmitters are the additional power and size requirement. Existing contribution quality radio microphones are constant carrier devices and may be required to transmit continuously for 6 hours, while worn under a performers costume. With the extra power requirement of A to D conversion and digital compression plus the space taken by discrete circuitry, the real solution is for large scale integration of the functions.

Existing integrated digital voice coding technology is not suited to the high quality, wide bandwidth signals required, both because of the low sampling rates and the speech specific digital compression algorithms used. A suitable integrated circuit with the wide bandwidth, high sampling rate and benign compression algorithm required, will enable the implementation of digital technology to produce benefits, both for the user and in terms of spectrum efficiency. However due to the relatively small size of this market by comparison to that of say GSM, the financial viability of the R and D investment in low power high quality digital coding and modulation may be dependent upon other markets.

Current analogue systems have been shown to be capable of spectrum sharing with other services and also able to use narrow frequency band allocations. To produce a spectrum efficient digital radio microphone system, a primary allocated frequency band or bands would be required, capable of handling at least 50 simultaneous transmissions from one site.

Without this allocation, the development of digital radio microphones will be discouraged.

10. SIMPLE AUDIO LINKS

These devices come in many forms :

1. High power radio microphone (1 - 4 watts) for sporting events where a conventional radio microphone has insufficient range.

A detailed specification for two high power radio microphone/audio links for outside broadcast use (contribution quality) is in Appendix H & I.

2. As a relay to an outside broadcast truck or studio using a conventional radio microphone receiver as an input to the link.

3. As a “radio” mixer incorporating a number of radio microphone receivers and transmitting a single mono or stereo transmission.

4. Any of the above but incorporating a narrow band (12.5 kHz) talkback or cue system in the same physical case (see Appendix J).

5. Taking the output of a mixing desk to remote amplification equipment.

As the physical size and powering of the equipment is of less importance than a radio microphone (which often needs to be hidden in the costume of the user) codecs and circulators along with directional aerials can be used to enhance both performance and spectral efficiency of these systems. Modulation techniques may be tailored to mono, stereo or quadraphonic channels.

Frequency Range for Simple Audio Links

Equipment is commercially available from 48 MHz through to 3.5 GHz. Many of the broadcasters will use VHF or UHF broadcasting spectrum co-ordinated via their national administrations.

APPENDIX A

CURRENT FREQUENCY ALLOCATIONS

FREQ.(MHz)	AUSTRIA	DENMARK	NORWAY	UK	FINLAND	FRANCE	GERMANY	SPAIN	CH
920.00									
910.00									
900.00									
890.00									
880.00									
870.00									
860.00				■					■
850.00								■	■
840.00								■	■
830.00									■
820.00							■		■
810.00		■	■				■		■
800.00		■	■				■		■
790.00							■		■
780.00									■
770.00									■
760.00									■
750.00									■
740.00									■
730.00									■
720.00									■
710.00									■
700.00									■
690.00									■
680.00									■
670.00									■
660.00									■
650.00									■
640.00									■
630.00									■
620.00									■
610.00									■
600.00									■
590.00									■
580.00				■					■
570.00									■
560.00									■
550.00									■
540.00									■
530.00									■
520.00									■
510.00				■					■
500.00				■					■
490.00									■
480.00				■					■
470.00									
460.00									
450.00									
440.00									
430.00									
420.00									

410.00									
400.00									
390.00									
380.00									
370.00									
360.00									
350.00									
340.00									
330.00									
320.00									
310.00									
300.00									
290.00									
280.00									
270.00									
260.00									
250.00									
240.00									
230.00									
220.00									
210.00									
200.00						ON STUDY			
190.00									
180.00									
170.00									
160.00									
150.00									
140.00									
130.00									
120.00									
110.00									
100.00									
90.00									
80.00									
70.00									
60.00									
50.00									
40.00									
30.00									

APPENDIX B

FREE FIELD LOSSES

VARIATION OF FREE FIELD LOSSES (dB) WITH FREQUENCY AND DISTANCE 20 log (23.87/FD)

Distance (metres)	Frequency (MHz)								
	200	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
0.25	6.4	10.0	12.5	14.4	16.0	17.3	18.5	19.5	20.4
0.5	12.4	16.0	18.5	20.4	22.0	23.3	24.5	25.5	26.4
1	18.5	22.0	24.5	26.4	28.0	29.3	30.5	31.5	32.4
3	28.0	31.5	34.0	36.0	37.5	38.9	40.0	41.0	42.0
5	32.4	36.0	38.5	40.4	42.0	43.3	44.5	45.5	46.4
10	38.5	42.0	44.5	46.4	48.0	49.3	50.5	51.5	52.4
20	44.5	48.0	50.5	52.4	54.0	55.4	56.5	57.5	58.5
40	50.5	54.0	56.5	58.4	60.0	62.4	62.5	63.5	64.5
50	52.4	56.0	58.5	60.4	62.0	63.3	64.5	65.5	66.4

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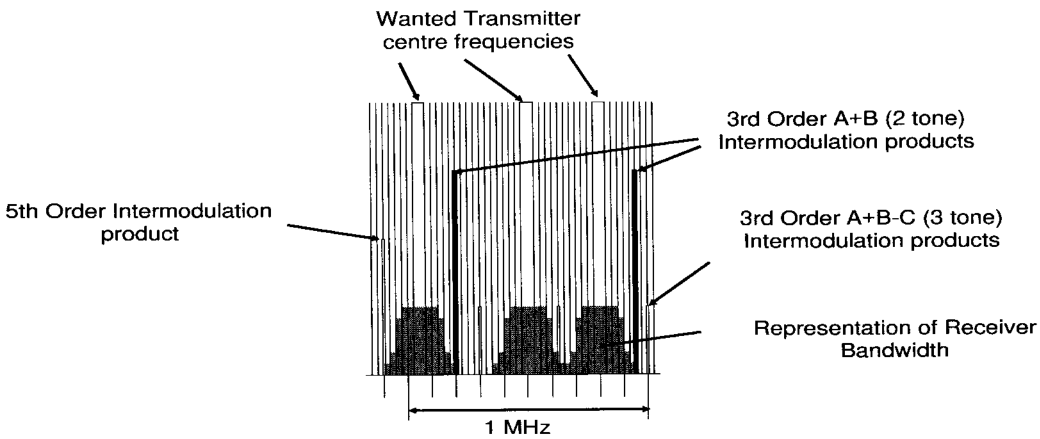
APPENDIX C

MULTICHANNEL SPECTRUM PLOTS SHOWING INTERMODULATION PRODUCTS AND INTERLEAVING

KEY to multichannel plots



Within a 6.5 MHz frequency conventional frequency allocation has been limited to 6, 200 kHz radio microphone channels, based on a grid of 200 kHz.

The following graphs show how the spectrum utilisation can be maximised by using a 25 kHz grid.

The following assumptions have been made in the development of this interleaving plan:

1. 3rd order A+B intermodulation products must not fall within 150 kHz of the centre frequency of any other frequency in the same set.

2. 5th order A+B intermodulation products must not fall within 150 kHz of the centre frequency of any other frequency in the same set.

3. 3rd order A+B-C intermodulation products must not fall within 50 kHz of the centre frequency of any other frequency in the same set.

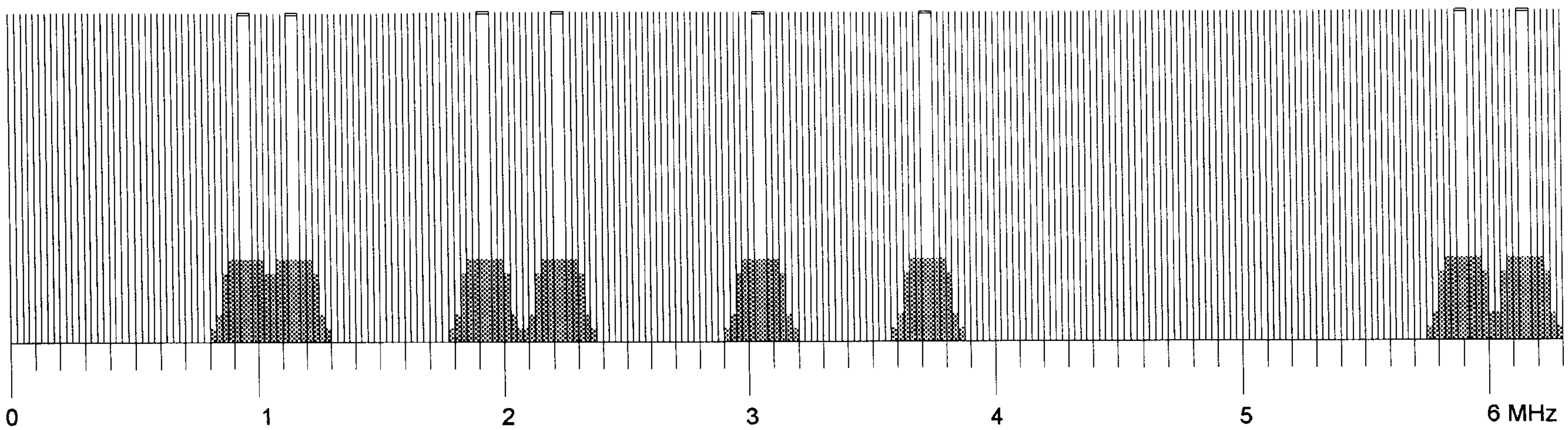
4. No two sets are operated in the same hall or studio, but may be used in adjacent hall or studio.

No frequency scale numbering is shown as the plan may be utilised within any 6.2 MHz band (this allows the plan to avoid the vision carrier in a 8 MHz TV band). Each small division on the graph represents a 25 kHz step. The scale divisions are 100 kHz with larger markers at 1 MHz.

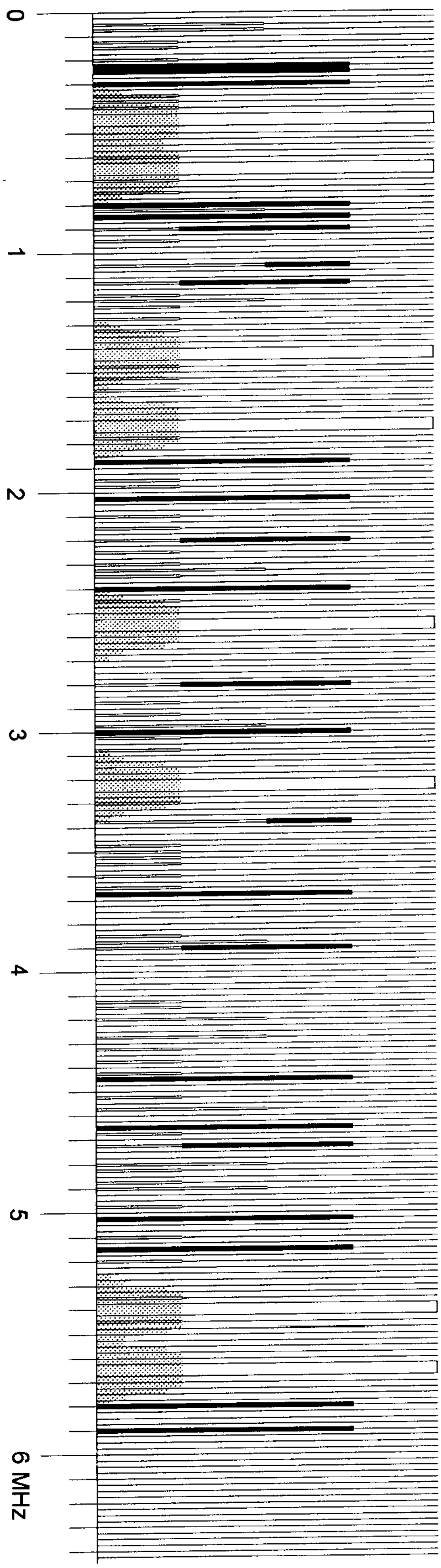
Transmitter centre frequency

The white line marking the centre frequency of the channel has a shaded area representing the receiver bandwidth at its base. These channel markers and bandwidth shading also distinguish the sets in the composite plan.

3rd order A+B intermodulation products are indicated by the tall thick black lines.
5th order A+B intermodulation products are indicated by the medium height lines.
3rd order A+B-C intermodulation products are indicated by the short lines.

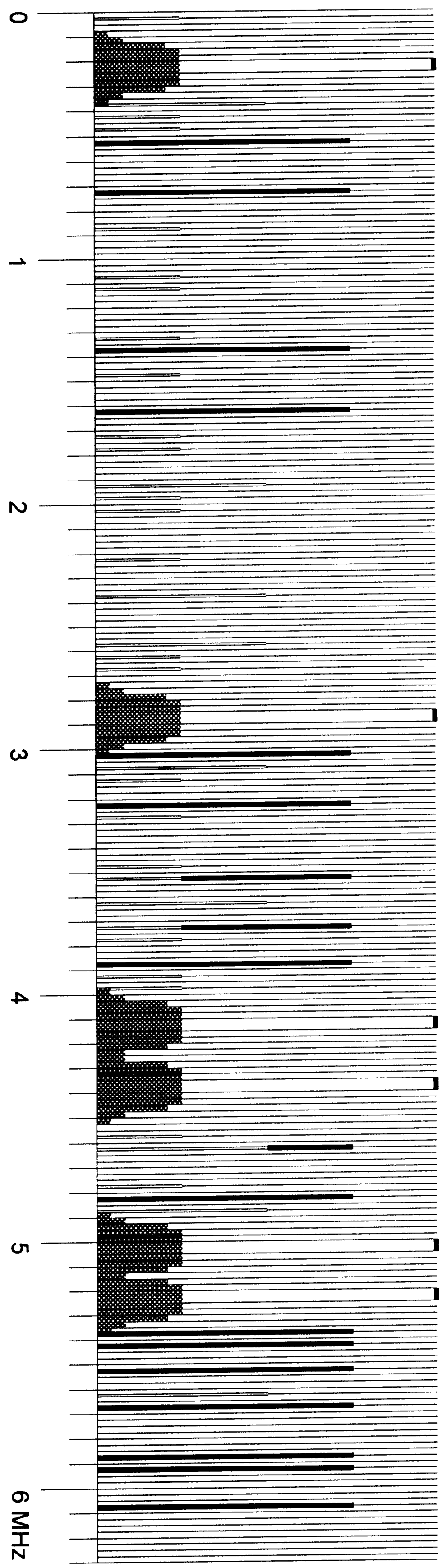


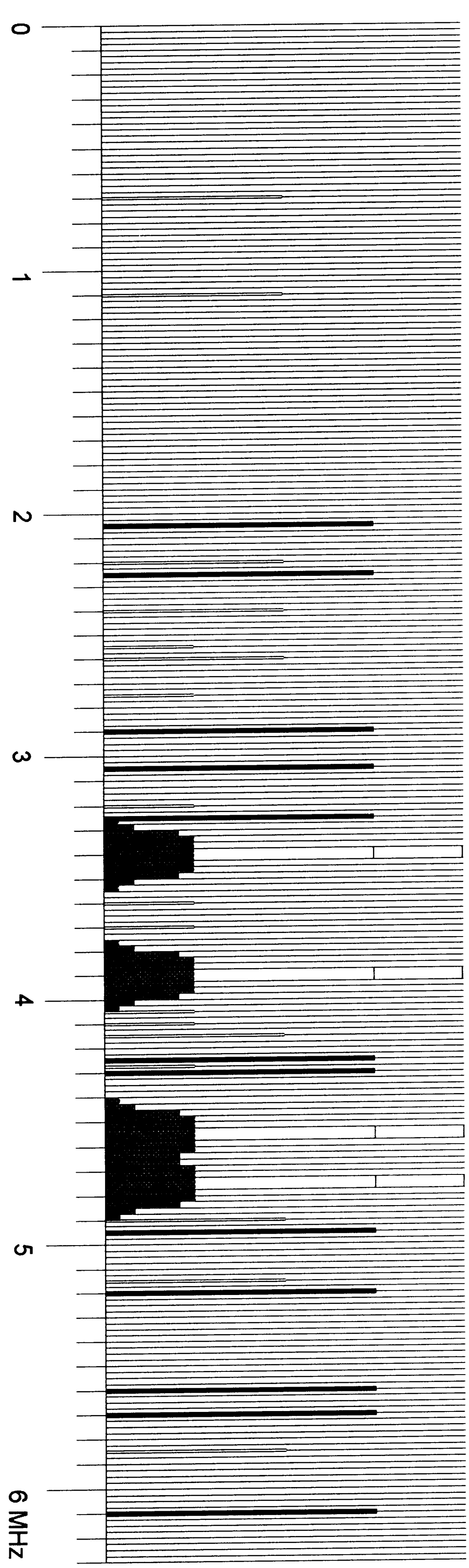
ɛt 1 8 Channels. No intermodulation products shov



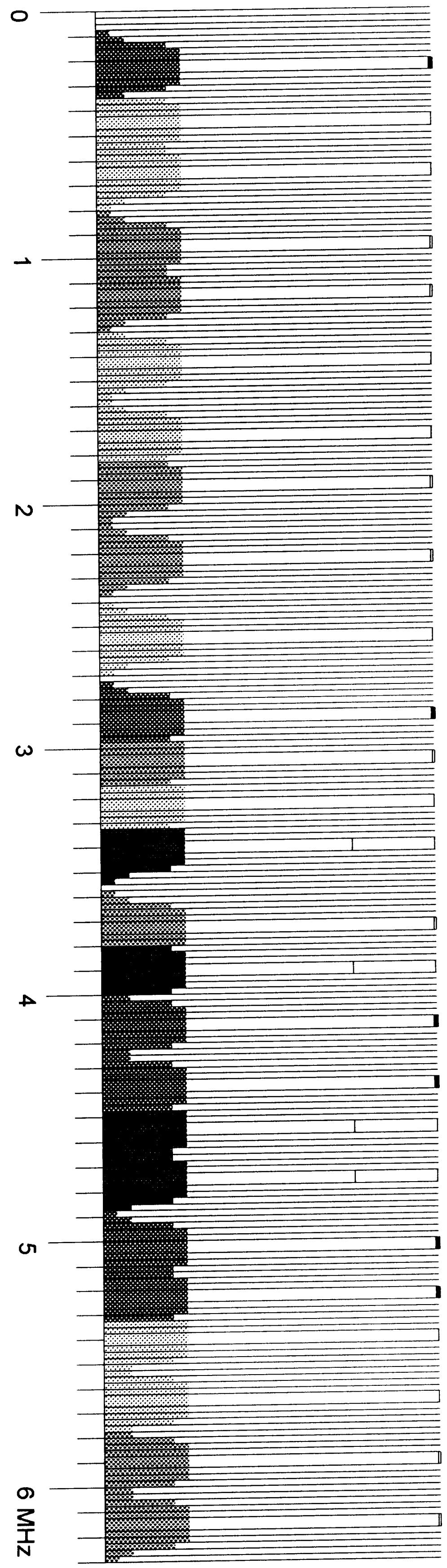
Set 2 8 Channels. Repeat of set 1, offset by 500 kHz intermodulation products shown

Set 3 6 Channels. Showing intermodulation products





Set 4 4 Channels. Showing intermodulation products



Sets 1, 2, 3 and 4 Overlaid.
Showing interleaving of carrier frequencies.

APPENDIX D

INTERMODULATION

Intermodulation is the generation of unwanted spurious output by the interaction of two or more signals in a non linear device.

Transmitter intermodulation

In a radio microphone transmitter the non linear device is usually the power output stage, which for reasons of efficiency is typically operating in class C. If two transmitters are physically close (<1.0 m), they will interact producing a series of spurious signals.

Although a whole series of sum and difference spurious frequencies are produced, it is only those which are close to the original transmitter frequencies that will be a problem. These signals take the form:

$2f_1-f_2$, $2f_2-f_1$, $3f_1 - 2f_2$, $3f_2 - 2f_1$

Substituting actual numbers will make the mechanism clearer:

If f_1=100MHz and f_2=101MHz:

$2f_1-f_2$ = 99MHz , $2f_2-f_1$ = 102MHz , $3f_1-2f_2$ = 98MHz, $3f_2-2f_1$ = 103MHz

These intermodulation products are known as 2 tone or A+B type. It can be seen that the intermodulation products occur at intervals equal to the frequency difference of the transmitters. The pair of spurious signals nearest the transmitter carriers are 3rd order (from the sum of the order of the terms): $\underline{2}f_1-\underline{1}f_2$. The next pair out are 5th order: $\underline{3}f_1-\underline{2}f_2$. Higher order products are not usually produced even under extreme operating conditions. If the two close transmitters are also similar in frequency (within 1 MHz), the intermodulation products may be of appreciable amplitude.

Miniature circulators or directional couplers are now available as a spin-off from the 800 - 900 MHz cellular phone market and provide a useful reduction in transmitter generated intermodulation products for units operating at these frequencies. Unfortunately the size and availability of these devices at lower frequencies currently rules out their use in miniature radio microphone transmitters below 750 MHz, and so for most of the operating frequencies of radio microphones the transmitter generated intermodulation products are allowed for in multichannel planning.

A further 3rd order spurious intermodulation signal will be generated when a third transmitter is introduced. This is known as a 3 tone or A+B-C type and takes the form :

$f_1+f_2-f_3 = f_x$ where f_x is a fourth channel.

In practice this type of intermodulation is not normally a transmitter problem, due to the difficulty in getting three transmitters physically very close and the necessarily greater frequency separation of any third transmitter. The transmitter two tone or A+B intermodulation products are the main transmitter concern in any multichannel frequency plan.

Receiver intermodulation

For a single receiver it is the linearity of the input stage(s) and the large signal handling capability of the first mixer that determines the level of intermodulation products generated within the receiver. A highly selective input filter should ideally protect the receiver from other unwanted signals.

In a multichannel system the input stage is usually part of the antenna distribution circuit or even in a masthead pre-amp. The input filter bandwidth should be tightly tailored to only accept the wanted radio microphone transmitter signals, (especially needed when operating near a used TV channel). Both A+B and A+B-C 3rd order intermodulation products can be produced within the receiving system, however serious intermodulation will normally occur only under strong input overload conditions. Once the receiver input has been driven into hard overload (blocking), it’s sensitivity to wanted signals falls and 5th order intermodulation products also become a problem within a multichannel set.

The proposed requirement for multichannel receiving systems to have a tuning range of over 20 MHz conflicts with the need for tight input filtering. This reduces the protection of the system against adjacent strong interfering signals and minimises the risk of receiver generated intermodulation products.

APPENDIX E

GRID SPACING

It is common practice for the PTT organisation or licensing authority of a country to impose a grid or raster onto a frequency band for the purpose of allocating operating frequencies to transmitting equipment. The grid spacing has often been either a mathematical progression or chosen to match the channel bandwidth of the transmitters, rather than being chosen to optimise the use of the band by allowing closer intermodulation spacing. This is particularly relevant in the case of multichannel radio microphone systems where the particular constraints of low power and large numbers of transmitters operating simultaneously require careful channel planning to reduce intermodulation interference. Constraining the radio microphone transmitter frequencies to a coarse grid makes inefficient use of the spectrum available.

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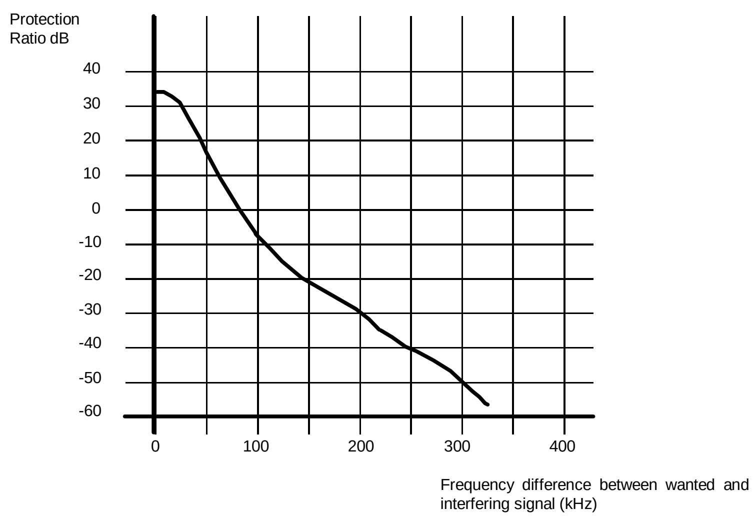
APPENDIX F

RF PROTECTION RATIO

The RF protection ratio of a receiver is a function of the frequency spacing between wanted and unwanted signals and depends mainly on the selectivity of the receiver, however, the characteristics of the limiting and demodulator circuits of the receiver and the received signal strength also have an effect.

The standard receiver protection ratio measurement is defined in CCIR publication 796-1. The strength of a modulated interfering signal that produces a decrease in signal to noise ratio of an unmodulated wanted signal from -56 dB to -50 dB is measured, as the frequency difference between the signals is reduced. This is then compared to the strength of the wanted signal and the ratio of the two plotted against frequency difference.

Typical Protection Ratio Curve



To summarise:

The closer in frequency the interfering signal is to the wanted signal, the stronger the wanted signal must be to maintain the required signal to noise ratio.

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APPENDIX G

TYPICAL CONTRIBUTION QUALITY RADIO MICROPHONE

The following information is supplied by courtesy of Audio Engineering Ltd, manufacturers of MICRON radio microphones.

RF TRANSMISSION SYSTEM

Carrier frequency range (to order)	150 to 950 MHz
Switched frequency options	UHF 2 - frequencies
	VHF 3 - frequencies
Switching range	VHF 1.2 MHz
	UHF 4.5 MHz
Modulation system	100F3EGN
Pre/de-emphasis	50 µS
Minimum channel spacing	200 kHz
Deviation at ALC threshold	15 kHz ± 1.0 dB
Companding system	CNS

TRANSMITTER

PEAK SIGNAL TO NOISE RATIO (RMS A weighted, measured at receiver high level output)

CNS Strong signal (Tx input terminated)	>100 dB
CNS Frequency response	50 to 16 kHz ± 2dB

AUTOMATIC LEVEL CONTROL SYSTEM

Gain control range:	automatic 50 dB manual 40 dB
Attack time	25 mS/10 dB
Recovery time:	transient overload 10 dB/S sustained overload 0.5 dB/S
Distortion (1 kHz tone @ 40 dB overload)	<0.3 % THD

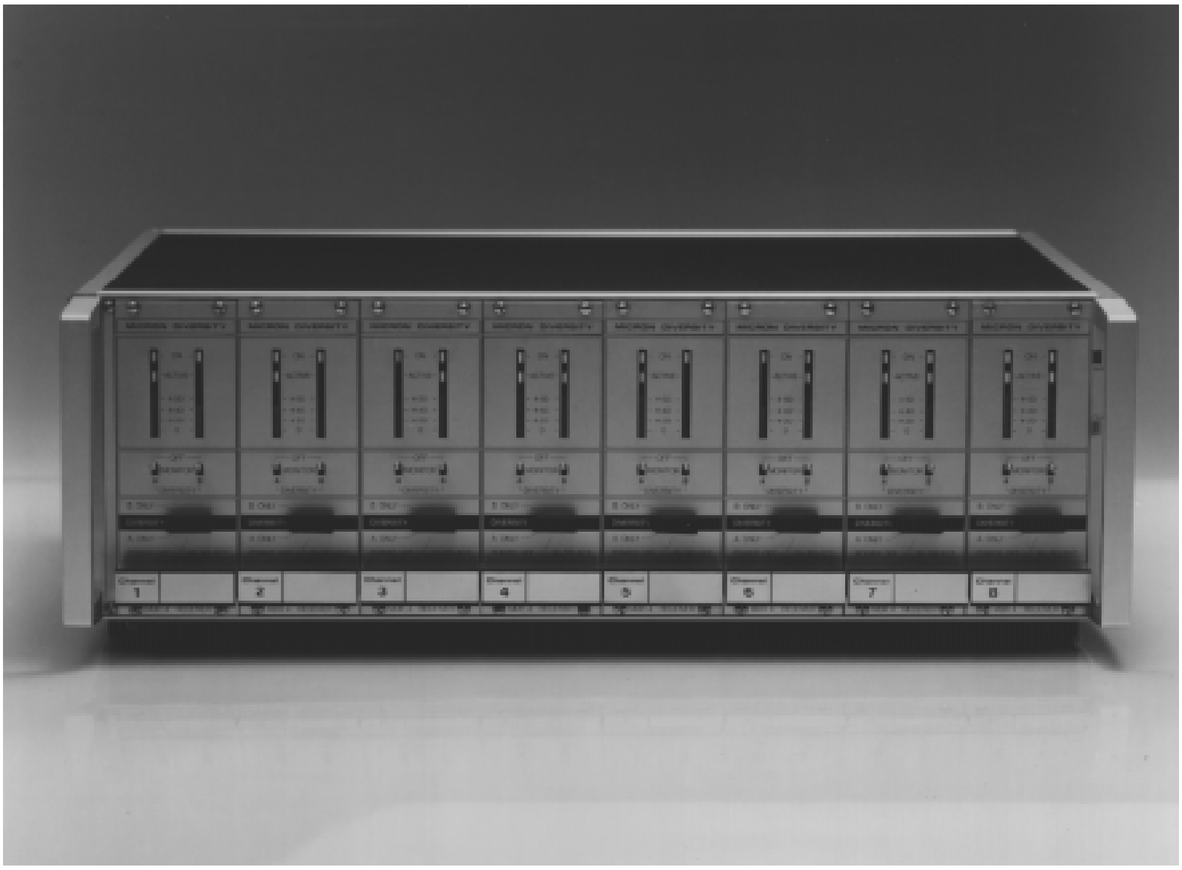
Note: ALC system allows short transients to pass (up to + 6 dB).

CONTROLS

Line-up tone enable	push button
ALC disable/Volume indicator enable	latching push button
SET level (modulation sensitivity)	Screwdriver pre-set
Battery test	line up tone button + ALC button
‘0’ light	>7.6 V
‘-10’light	>7 V
Both lights flash	<6.5 V
Transmitted low-battery early warning	Rx tuning indicator flashes at <6.5 V nominal

RECEIVER

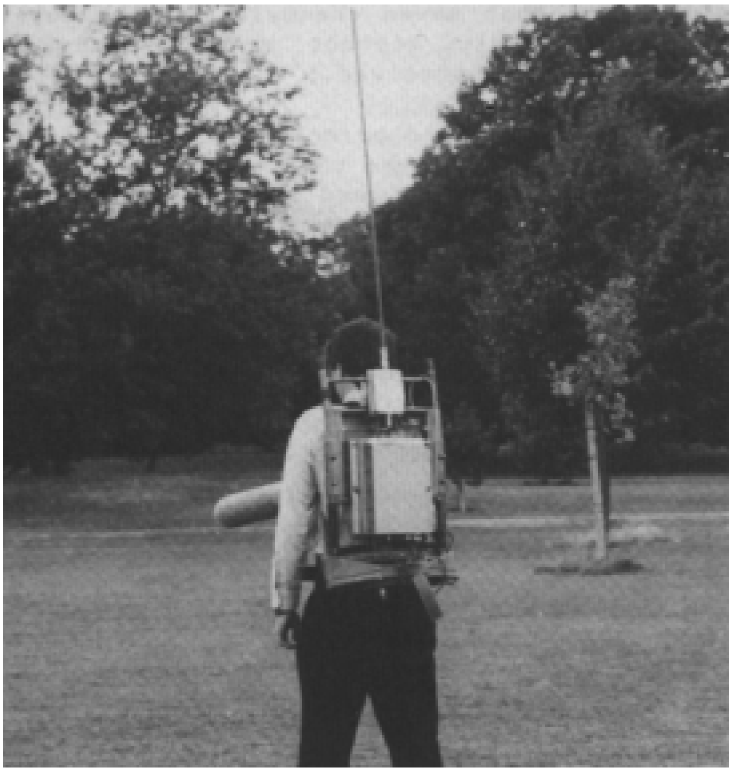
Adjacent channel rejection	>90 dB
Muting level	0.7 μV



APPENDIX H

TYPICAL CONTRIBUTION QUALITY HIGH POWER AUDIO LINK

The equipment detailed in the following section is not readily commercially available, but was developed and built by the BBC.



The following information is supplied by courtesy of the BBC.

SPECIFICATION

<u>Transmitter TM3P/9</u>

RF output power (50 ohm)	1 or 4 watts nominal, switch selectable
RF output (>± 100 kHz from f_c)	<-65 dBc (harmonic & non-harmonic)
f_f accuracy	± 3 kHz
Input line-up sensitivity	
Range L	+18 to -12 dBu
Range 1	-10 to -40 dBu
Range 2	-40 to -70 dBu
Audio Processing	
Input filter: Switchable High Pass	Out
	150 Hz
	300 Hz > 20 dB/octave
Low Pass	15 kHz (>60 dB attenuation at 35 kHz)

Input peak limiter, applied signal, 20 dB above peak deviation at 1 kHz

Attack time	+1.5 dB after 3.5 msec.
40 dB reduction in level	
Recovery time	nom.value (-1dB) after 1 second
Phantom power	+48 Vdc (14 mA limited), selected on sensitivity switch
Headphone Monitor	2 Vrms from 50 ohms source
Supply Current	400 mA typical (4 watts RF O/P) 290 mA typical (1 watt RF O/P)
Weight	1kg approx.

<u>Receiver RC4P/10</u>

RF input	500 mV maximum
Mute level	Adjustable, 1-200 μV
AGC	300 μV threshold, 40 dB range
Noise figure	$\leq$9 dB
Audio output	+8 dBm unbalanced into 600 ohms for 15 kHz peak deviation at 100 Hz rate
Switchable line-up tone;	1 kHz, 0 dBm
Headphone Monitor	Variable level into high impedance
Supply current	400 mA typical
Weight	1kg approx.

<u>Overall Link, Tx-Rx</u>
(Transmitter set to deliver 0 dB RF out)

Line up tolerance	0 ± 1dB
Frequency Response	50 Hz-12 kHz ±0.75 dB 40 Hz-15 kHz $\pm$1.0 dB (PPM ‘4’) 50 Hz-12 kHz $\pm$1.5 dB } (PPM ‘4’) 40 Hz-15 kHz $\pm$2.0 dB } (less 20 dB)
Total harmonic distortion	$\geq$46 dB down on PPM ‘6’
Signal - Noise ratio	57 dB 4W @ 1 mV RF at Receiver I/P 43 dB 4W @ 20 μV RF at Receiver I/P
Low battery indication	When battery pd. falls below 21.7 V, 19 kHz tone is transmitted which flashes the signal-strength bargraph on the receiver.
Operating temperature	-10^o C to +40^o C

APPENDIX I

TYPICAL HIGH POWER NON CONTRIBUTION QUALITY AUDIO LINK

The following information is supplied by courtesy of Sound Broadcast Services.

TRANSMITTER

Transmitter Power level	0 to 5 watts
Frequency Range *	800 - 900 MHz
Power output variation	+10 %/-2 %
Output Impedance	50 Ohms
Harmonic and spurious outputs	<-60 dBc
Input Voltage range	230 V_{ac}±10 %
Input Sensitivity for 75 kHz deviation	-10 to + 20 dBm
Audio frequency response (no pre-emphasis)	±0.5 dB (5 Hz - 100 kHz)
Audio frequency response relative to 50 µS curve	±0.5 dB (50 Hz - 15 kHz)
Total harmonic distortion	<0.2 % (typ. 0.17%)

* Broadcast transmitter design is usable over any 15 MHz band, between 800 - 900 MHz (in 50 kHz steps) without tuning.

Option version allows broadcast transmitter or other equipment to be controlled via a link.

RECEIVER

Input Impedance	50 Ohms
Sensitivity for 10 dB SINAD	3 uV
S/N Ratio @ 1mV input	-72 dB (50 Hz-15 kHz)
Minimum Sensitivity for carrier detect.	20 µV
Audio Output at 75 kHz deviation	-20 to +10 dBm
Audio distortion	<0.2 %
Input voltage 230 V_{ac}±10 %	

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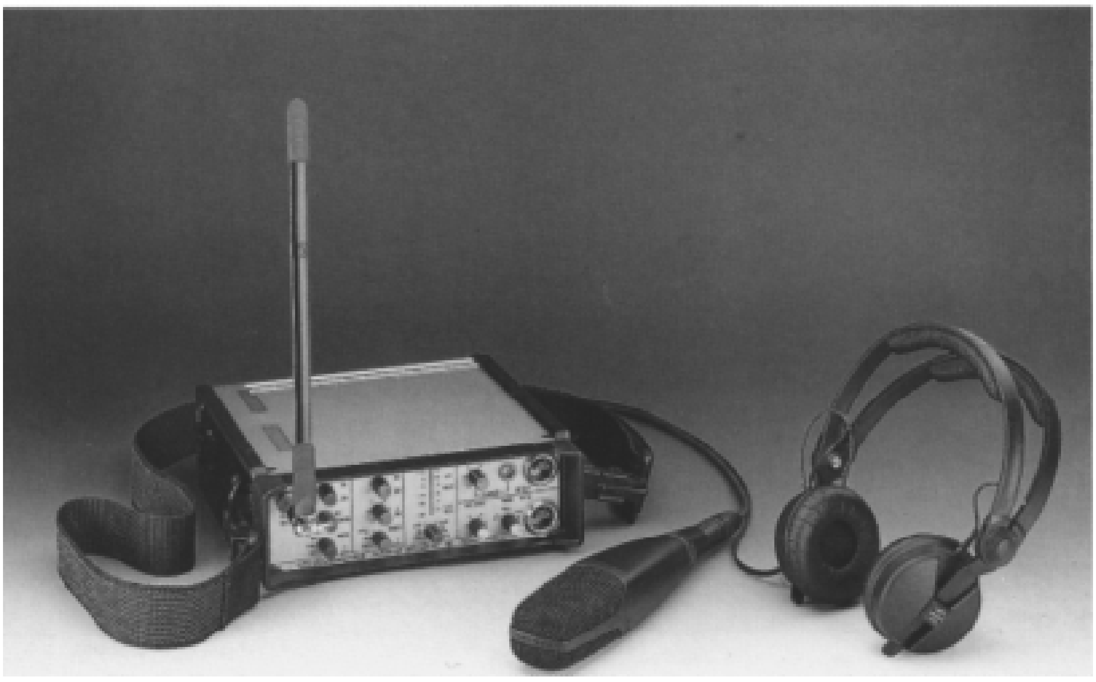
APPENDIX J

TYPICAL CONTRIBUTION QUALITY HIGH POWER AUDIO LINK WITH NARROW BAND CUE RECEIVER

The following information is supplied by courtesy of Sennheiser



TRANSMITTER

Frequency range	580 - 790 MHz
Selectable frequencies	max. 16
Switching Bandwidth	185 MHz
RF output Power into 50 Ohm	3 W and 1 W switchable
Frequency stability (-10°C to +65°C)	$\leq\pm$ 2.5 kHz
Suppression of spurious and harmonics	>85 dB
Spurious and harmonic emission	$\leq$ 10 nW

RECEIVER

Frequency range	470 - 526 MHz
Switchable frequencies	max. 16
Switching bandwidth	approx. 17 MHz
Intermediate frequencies	21.4 MHz, 62.3 MHz
Channel spacing	20 kHz minimum
Nominal deviation (= peak deviation)	2.8 kHz
De-emphasis	6 dB/octave
AF output voltage at nominal swing	1.55 V into 600 Ohm
Frequency response (-3 dB)	300 Hz to 3 kHz
Audio distortion at nominal swing and 1 kHz Modulation Frequency	3% (typ. 1%)
Compandor System	HiDyn (defeatable)
Sensitivity for S/N = 26dB	
(nom. deviation, mod. frequency 1 kHz, CCITT)	1 µV
S/N Ratio (CCITT, without HiDyn)	50 dB/300 µV RF
S/N Ratio (Unweighted, with HiDyn)	80 dB/15 µV RF
Adjacent channel rejection	70 dB
Image rejection	90 dB
Spurious rejection	66 dB
Interference radiation at antenna input	-70 dBm
Power requirements	10.5 - 15 V_{dc}
Current consumption	approx. 120 mA
Operating Voltage	
NiCad accu GZB 20	12 V/4 Ah
Battery life (3 W + receiver)	approx. 3 h
(1 W + receiver)	approx. 5.5 h
(receiver only)	approx. 25 h

ACKNOWLEDGEMENTS

Radio Microphone Systems for a High Channel Density	by Stefan Frese, AKG Akustische, Vienna
Multichannel Radio Microphone Systems	by Kurt-Walter Rüdiger, Beyer dynamic, Heilbronn
Extension of the Dynamic Range of Radio Microphones	by Wilfried Pohl and Erhard Werner Sennheiser Electronic KG, Wedemark
Improvement of Multichannel Radio Microphone Operation by use of Advanced Receiver Techniques	by Erhard Werner, Sennheiser Electronic KG
Mobile Communications Engineer	by William C Y Lee
ETSI STC RES08 WG3 Spectrum Survey	
Multichannel Radio Microphone use	by John Wykes, Audio Engineering
BBC Engineering Design Information	by John Sykes, BBC
ETSI STC RES08 Working Group 3	