



**DOCUMENTS
OF THE NRPB**

**Possible Health Effects from
Terrestrial Trunked Radio
(TETRA)**

**Report of an Advisory Group on
Non-ionising Radiation**

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POSSIBLE HEALTH EFFECTS FROM TERRESTRIAL TRUNKED RADIO (TETRA)

Report of an Advisory Group on Non-ionising Radiation

CHAIRMAN: SIR RICHARD DOLL

This report from the Advisory Group on Non-ionising Radiation reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

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Executive Summary

INTRODUCTION

- 1 This report by the National Radiological Protection Board's Advisory Group on Non-ionising Radiation gives advice on possible health effects of Terrestrial Trunked Radio (TETRA). It has been prepared, at the request of Government, as a consequence of a recommendation by the Independent Expert Group on Mobile Phones (IEGMP) in May 2000 that 'as a precautionary measure, amplitude modulation around 16 Hz should be avoided, if possible, in future developments in signal coding'.
 - 2 The IEGMP recommendation was made because of the results of a number of studies on the effects of radiofrequency (RF) fields on the rate of loss of radiolabelled calcium from brain and other tissues. These studies, most of which were carried out in the late 1970s and early 1980s on isolated tissues, had suggested that when the RF signal was modulated at around 16 Hz the rate of calcium efflux was increased. IEGMP concluded that although no obvious health risk was suggested, as a precautionary measure, amplitude modulation around 16 Hz should be avoided, if possible.
-

THE TETRA SYSTEM

- 3 The system being used for commercial applications and by emergency services in the UK and in a number of other countries uses a network of base stations to serve terminals that are either vehicle mounted or in the form of separate handsets. Its operation results in power modulation of some of the RF signal at a pulse frequency of 17.6 Hz. As a consequence of the recommendation by IEGMP, concerns have been raised about the health implications of the use of this system.
- 4 In the UK a TETRA system is presently operated by Dolphin (for commercial use) and trials are under way by BT Airwave for the police and possibly for other emergency services. The system uses two carrier bands, between 380 and 395 MHz and between 410 and 425 MHz, although it is possible that other bands could be assigned if the demand grows. Fixed base stations serve mobile terminals that are in the form of hand portables (similar to mobile phone handsets) or built into vehicles (these are called mobiles by the police). The base stations provide the service either directly or indirectly via repeaters that are generally built into vehicles. The information from mobile terminals and repeaters is carried by the radio signal using phase modulation. The voice information is concentrated into bursts (or timeslots) 14.2 ms long, which occur every 56.7 ms (a frame) and this allows up to four users to communicate on the same frequency channel. This corresponds to a duty factor of a quarter and a pulse frequency of 17.6 Hz. It is notable that the signals from base stations are continuous, not pulsed, in contrast to those from mobile terminals and repeaters, that are pulsed.
- 5 In the most common mode of use, the network continually adjusts the power radiated by a TETRA mobile terminal to the minimum necessary to maintain radio

contact during a call. This technique of adaptive power control (APC), which conserves the battery of a hand portable, is also a feature of GSM (Global System for Mobile Communication) mobile phones used commonly in the UK and around the world.

PHYSICAL DOSIMETRY

- 6** Exposure to RF fields from the TETRA system can arise in a number of different ways. As hand portables are not intended for use by the general public, the predominant exposure from these devices will arise in the course of work. Similarly, occupational users will normally receive greater exposure from vehicle-mounted terminals than will the general public. Exposure of workers in other occupations may also occur in the vicinity of base station antennas, particularly when they are located at rooftop sites. The exposures of the general public, at normally accessible positions in the vicinity of TETRA base stations, will be small fractions of the exposure guidelines and will be comparable with exposures due to the ambient field strengths arising from the operation of other telecommunication systems.
 - 7** Guidelines advising limits on exposure to RF radiation are expressed in terms of specific energy absorption rate (SAR)*. Little work has, however, been published on the assessment of SAR in the head from TETRA hand portables under simulated conditions of use. The results of very limited experimental work known to the Advisory Group suggest that when the present generation of hand portables, with 1 W and 3 W power outputs, are operating at full power, the exposure of the head will be below the guidelines on exposure limits recommended for occupational exposure by NRPB and by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Actual SAR values would commonly be less than those determined experimentally at maximum operating power, both because of APC and because most calls will be short. The average output powers of these hand portables are 0.25 W and 0.75 W; less than the 1.5 W average power output of the analogue hand portables presently being used by the police. This suggests that exposure from the TETRA hand portables will generally be less than that from the present system.
 - 8** It is considered possible by the Advisory Group, that if future developments in the TETRA system required the use of more than one of the four timeslots in the frame (as for data or video transmission), then under these circumstances SARs could be up to four times larger and, for the 3 W hand portables, could exceed exposure guidelines for workers. The use of more than one timeslot could, in addition, change the frequency of pulse modulation. The guidelines could also be exceeded for a mobile terminal of 10 W and above if the head were placed near to the antenna. On the basis of existing data, careful thought needs to be given to the design and conditions of use of any future systems with respect to ensuring compliance with exposure guidelines.
-

* SAR: the rate at which energy is absorbed by unit mass of tissue in an electromagnetic field; measured in watts per kilogram ($W\ kg^{-1}$) (relevant guidelines average exposures of the head over 10 g and 6 minutes).

BIOLOGICAL EFFECTS

- 9** The initial report describing the phenomenon of calcium efflux was published in 1975. It suggested that exposure of isolated chick brain hemispheres to RF fields modulated at around 16 Hz, at levels too low to cause bulk heating, nevertheless could cause a small increase in the movement of calcium ions. Subsequent studies, some by other research groups but with essentially the same methodology, reported similar findings using this and a variety of other preparations and exposure conditions. Generally, however, no obvious effects were found using the carrier frequency alone, and the phenomenon occurred only with particular combinations of modulating frequency, carrier frequency and power density, giving rise to particular SARs.
- 10** The existence of changes in calcium efflux, and their significance if they occur in living tissue, are much disputed. The design and interpretation of the early studies were not ideal and they were predominantly carried out using non-living tissue. Since the early 1980s a number of generally better designed studies have failed to detect an increase of calcium efflux from tissues as a result of RF exposure under a variety of conditions and modulations. If the phenomenon is biologically significant, concomitant changes would be expected in the functions of nervous tissues that depend on the movement of calcium ions, but none has been unambiguously shown to occur. For example, changes in neuronal excitability have been reported but mostly under conditions of exposure to RF fields sufficient to cause biologically significant heating. Similarly, changes in brain wave activity in animals may be largely attributable to subtle heating effects. Suggestions that pulsed RF fields could trigger epileptic fits or otherwise affect epilepsy sufferers appear to be unjustified.
- 11** There do not appear to be any studies on people that provide direct information on health effects of exposures to RF fields at about 16 Hz modulation. Overall, research on exposure to low level RF radiation in general has not provided any persuasive evidence that it causes disease in people. Although, when viewed as a whole, the epidemiological research that has been carried out does not give cause for concern, it has too many limitations to provide assurance that there is no hazard.
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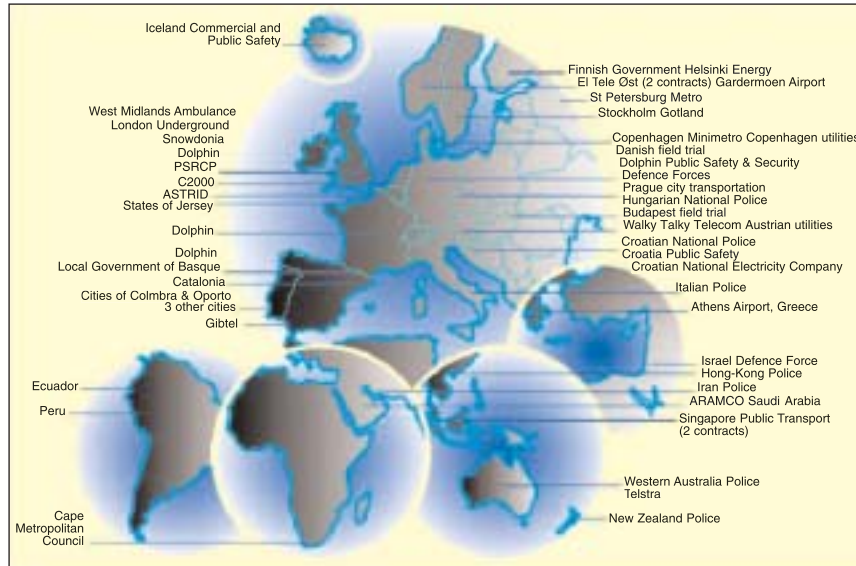
CONCLUSION

- 12** It is recognised that calcium plays an important role in many biological processes, especially in the function of nerve cells. Moreover, as the Independent Expert Group on Mobile Phones pointed out, there is evidence that RF fields, amplitude-modulated at about 16 Hz, may influence the leakage of calcium ions from tissues. However, findings have been contradictory; they are more uncertain for living than for non-living tissue, and no associated health risk has been identified. It is notable that the signals from TETRA base stations are not pulsed, whereas those from mobile terminals and repeaters are. Although areas of uncertainty remain about the biological effects of low level RF radiation in general, including modulated signals, current evidence suggests that it is unlikely that the special features of the signals from TETRA mobile terminals and repeaters pose a hazard to health.
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INTRODUCTION

- 1** In May 2000, the Independent Expert Group on Mobile Phones (IEGMP) issued a report on *Mobile Phones and Health* (IEGMP, 2000). Among other things, this report reviewed studies relating to possible health consequences of exposure to radio-frequency (RF) radiation from mobile phones and their associated base stations. It also made recommendations for further work that could be carried out in order to improve the basis for sound advice.
- 2** Included in the report by IEGMP was a review of a number of laboratory studies that had examined the effects of exposure to RF radiation on the rate of loss of radiolabelled calcium (efflux) from brain tissue. Most of these studies had been carried out in the late 1970s and early 1980s. Several reported that exposure to RF radiation alone had no obvious effect, but, when the signal was amplitude modulated, there was an increase in the rate of calcium efflux. In some cases, a number of different frequencies of amplitude modulation (usually between 1 and 30 Hz) were employed and a maximum effect was obtained around 16 Hz. This led to the view that modulation at or near this frequency might be critically effective in its influence on cells and tissues of the nervous system. Some subsequent studies in other laboratories had, however, failed to corroborate these results.
- 3** IEGMP concluded that the findings in these studies had no obvious relevance to mobile phone technology, where the amplitude modulation at frequencies within the critical frequency band is very small. Even if such effects were to occur, their implications for cell function are unclear and no obvious health risk has been suggested. Nevertheless, IEGMP concluded that 'as a precautionary measure, amplitude modulation around 16 Hz should be avoided, if possible, in future developments in signal coding'.
- 4** As it happens, a telecommunication system is being installed by BT Airwave for use by the emergency services in the UK. This system is based on the TETRA (Terrestrial Trunked Radio) technical standard, which has been used by another UK network operator, Dolphin, since 1999, and which has been widely adopted elsewhere in Europe. The European Telecommunications Standards Institute (ETSI, 1999) has prepared the specification for TETRA and, since 1997, TETRA networks have been deployed throughout Europe and many other regions of the world, as shown in Figure 1.
- 5** TETRA operates at around 400 MHz, using a network of fixed base stations to serve mobile terminals that are in the form of hand portables (similar to mobile phone handsets) or built into vehicles (these are called mobiles by the police). The base stations provide the service either directly or indirectly via repeaters that are generally built into vehicles. The mobile terminals and repeaters transmit bursts of radiowaves, effectively causing power modulation at a pulse frequency of 17.6 Hz. It is intended that this system will be introduced for use by the emergency services widely across the UK. Questions have been asked as to whether there may be any possible health consequences to either users of the system or members of the public.
- 6** In the light of these concerns, the Government asked the Board of NRPB to provide advice on any implications for the health of TETRA users and others who may be exposed to its radio signals. The Board of NRPB subsequently asked its Advisory Group on Non-ionising Radiation to examine the issue.

FIGURE 1 Use of TETRA throughout the world in 2001 (courtesy of TETRA MoU Association)



- 7 The Advisory Group has as its terms of reference:
'to review work on the biological effects of non-ionising radiation relevant to human health and to advise on research priorities'
- 8 It was established in 1990 and remodelled in 1999 as a committee that reports directly to the Board of NRPB. The Advisory Group has issued six reports covering the possible health effects of the use of visual display units, exposures to ultraviolet radiation and extremely low frequency electromagnetic fields (the last relating specifically to cancer) (NRPB, 1992, 1994a,b, 1995, 2001, *in press*).
- 9 This report describes the TETRA system and reviews the experimental and epidemiological studies relevant to the assessment of any possible health effects that might arise from its use.
- 10 TETRA is a new digital system for mobile radio. It is designed to replace the older analogue radio systems that are currently used by professional and commercial organisations and it offers a variety of new facilities such as data communications and improved security. The principal features of the system, the carrier and modulation frequencies at which it operates, and the characteristics of relevant hand portables and base stations are reviewed in paragraphs 14–56.
- 11 The likely exposure of both users and members of the public to RF radiation as a result of operation of the TETRA system are then considered in paragraphs 57–77 and compared with the restrictions on exposure advised in published guidelines. Those guidelines currently operating in the UK are summarised in an appendix with a focus on the parts relevant to hand portables and base stations used for TETRA.
- 12 Experimental studies available for assessing any possible health effects arising from exposure to signals from TETRA are then examined (paragraphs 78–121). The calcium-efflux studies carried out in the late 1970s and 1980s are reviewed and placed in the broader context of more recent studies that have examined the effects of amplitude-

modulated RF radiation on brain tissue over a range of frequencies. Other relevant experimental studies are also considered, including those on neuroexcitability, effects on electroencephalograms (EEGs), epilepsy and other possible biological effects. The extent of epidemiological studies on exposures to RF radiation from mobile phones is summarised in paragraphs 122–128. Conclusion of biological effects are given in paragraphs 129–134.

13 Finally, recommendations for further work are given in paragraph 135.

TECHNICAL ASPECTS OF TETRA

14 This section discusses the engineering aspects of TETRA technology that influence the exposure of people from hand portables, vehicle-mounted terminals and base stations. TETRA is designed for speech communication and this report will largely be concerned with this aspect. However, TETRA can also be used for data communication and for transmitting video pictures and the signal waveform and average power may be significantly different when used in this way.

System architecture

15 TETRA networks have similar architectures to mobile phone networks. They consist of mobile terminals that communicate with each other through fixed base stations with antennas mounted above ground level on masts or buildings. This form of communication is referred to as Trunked Mode Operation (TMO) and is illustrated in Figure 2(a).

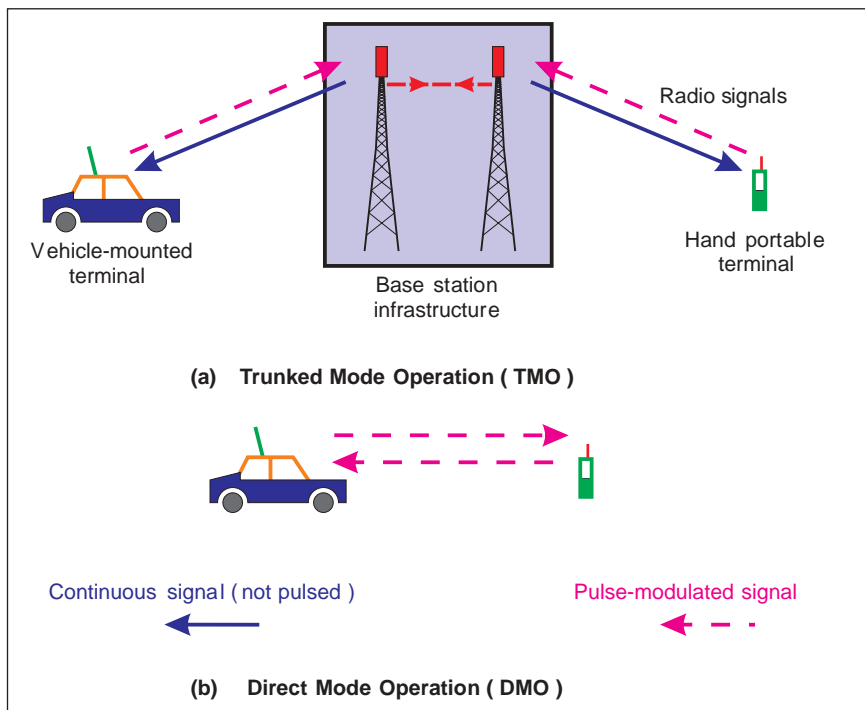


FIGURE 2 How communication takes place between mobile terminals in Trunked Mode Operation (TMO) and Direct Mode Operation (DMO)

- 16** The term mobile terminal covers both hand portables, that are normally held close to the head or waist of the user, and terminals built into vehicles such as police cars, ambulances, lorries or taxis, in which case an external antenna is used. The type of terminal used in a vehicle may also be used temporarily at a fixed location and is then referred to by the police as a 'fixed mobile'.
- 17** Operators place base stations at sites chosen to provide coverage throughout the whole area in which their customers are likely to be and the base stations are given sufficient capacity to ensure that the chance of a call being blocked by other users is minimal. Repeaters may be used to provide additional coverage.
- 18** The people who use TETRA networks have hand portables similar to mobile phones and these allow users to communicate with each other within what is essentially a private network. Calls to a group of specific individuals (a talk group) can be connected within around 0.5 second at the push of a single button.
- 19** TETRA mobile terminals are also able to operate in Direct Mode Operation (DMO). In DMO, a mobile terminal communicates directly with another mobile terminal so that the radio signals do not pass through the infrastructure of base stations, as shown in Figure 2(b). The Advisory Group has been informed that the majority of police calls over the BT Airwave network will use TMO. The Dolphin network and terminals presently only use TMO. DMO is not possible with conventional mobile phones, as used by the public.

Hand portables

- 20** TETRA hand portables and mobile phone handsets are similar in appearance, although the antennas of TETRA hand portables may be somewhat larger because of their lower operating frequency (longer wavelength). A typical TETRA hand portable is shown in Figure 3.
- 21** The radio signals are mainly radiated from the antennas, although some radiation is also emitted from the case. Helical antennas encapsulated in plastic shrouds are commonly used, as they are compact and flexible.

Remote speaker-microphones

- 22** A remote speaker-microphone allows hands-free use of a hand portable and is normally clipped to the shoulder/shirt pocket area of a police uniform but may also be held in the hand. It is connected via a cable to a hand portable held in a holster at waist level. The main exposure to the body should be from the antenna and case of the hand portable. The arrangement is illustrated in Figure 4.
- 23** Future systems may involve an antenna attached to the speaker-microphone, rather than to the hand portable. In this case the main exposure would move from waist level to nearer the shoulder and head.
- 24** Lightweight devices similar to the hands-free kits of mobile phones are also used. The earphone is attached to the ear (and may be under a helmet) and the microphone is clipped to the lapel. Both components are connected by a cable to a hand portable at waist level as before. The antenna is on the hand portable and so the main exposure would be at waist level (there might, however, be some exposure from the earphone as the result of RF current passing along the cable).



FIGURE 3 Typical TETRA hand portable (courtesy of Simoco)

Vehicle-mounted terminals

- 25** The terminal is mounted inside the vehicle and connected to an antenna mounted on the outside as shown in Figures 5 and 6. The Advisory Group has been informed by the Lancashire Police Authority that the antenna is mounted along the centreline of the roof in the majority of cars. However, the need for additional antennas on cars used largely on motorways can result in the TETRA antenna being mounted at the side of the roof. The Advisory Group understands that arrangements for ambulances have not yet been decided.

Base stations

- 26** Base stations are an essential part of the TETRA network used in Trunked Mode Operation. They need to provide full coverage throughout the UK. The time taken for the RF signals to travel from a mobile terminal to the base station limits its useful range to 56 km. In practice, however, other constraints such as signal quality significantly reduce this range and BT Airwave typically uses a maximum cell size of 8 km. Smaller cells are used in areas of high call traffic to ensure that one user is not blocked by others. An example of a TETRA base station installation is illustrated in Figure 7.

Possible Health Effects from Terrestrial Trunked Radio (TETRA)

FIGURE 4 Police officer equipped with a TETRA remote speaker-microphone on his chest and a hand portable mounted at waist level



FIGURE 5 Police car interior showing parts of the TETRA vehicle-mounted terminal





FIGURE 6 Police car showing the external antenna that is used with TETRA vehicle-mounted terminals



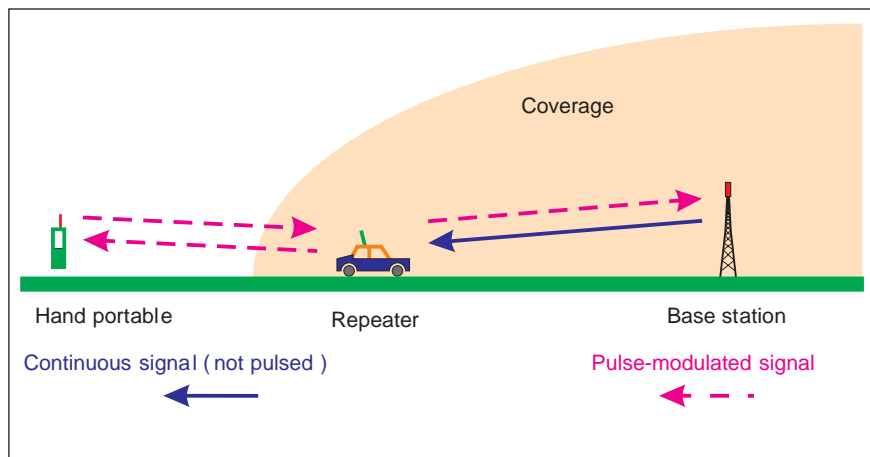
FIGURE 7 Antennas associated with a base station used for a TETRA network

- 27** Dolphin has about 1000 base stations in use throughout the country and in a trial by Lancashire Constabulary for the BT Airwave TETRA network 54 base stations are used. BT Airwave estimates that around 3000 base stations will be needed to provide UK-wide coverage for its network.

Repeaters

- 28** If the network of base stations does not provide sufficient coverage or capacity in a particular area, mobile repeaters can be used to provide additional coverage. The repeater relays calls from that area back into the network as shown in Figure 8. Repeaters have similar characteristics (power levels and antenna locations) to vehicle-mounted terminals but are normally dedicated to this particular use. Around 2000 repeaters are expected to be required by the UK police forces. Signals between the repeater and the base station have similar characteristics to those used in TMO, whereas those used between the mobile terminal and the repeater have similar characteristics to those used in DMO.

FIGURE 8 Use of a vehicle-mounted repeater to connect a hand portable to the base station network from a location beyond the coverage range or when greater capacity is needed



Frequency allocations

Proposed European allocations

- 29** The European regulatory body, CEPT (the European Conference of Postal and Telecommunications Administrations), has recommended a number of frequency bands for use with TETRA-based services. These are shown in Table 1.
- 30** Many of these frequency bands are currently used by other radio systems in the UK.

Current UK allocations

- 31** The Radiocommunications Agency regulates the use of the radio spectrum in the UK and the frequency bands shown in Table 2 are used by the two UK-based TETRA operators.
- 32** It seems likely that other frequency bands could be assigned to TETRA if the demand grew.

Frequency band (MHz)	
Mobile terminal transmit (uplink)	Base station transmit (downlink)
380-390	390-400
410-420	420-430
450-460	460-470
870-888	915-933

TABLE 1
Frequency bands
proposed for
TETRA in Europe

Operator	Frequency band (MHz)	
	Mobile terminal transmit	Base station transmit
BT Airwave	380-385	390-395
Dolphin	410-415	420-425

TABLE 2
Frequency bands
used by UK-based
TETRA operators

- 33** The older analogue systems currently in use by the police operate in two frequency bands: VHF in the range 140-150 MHz is used to cover wide areas with vehicle-mounted systems, whereas UHF in the range 450-460 MHz is used for more localised coverage with hand-held and body-worn radios.

Channel structure

- 34** Each band contains a number of frequency channels and these are paired so that the signal transmitted by a hand portable differs by a fixed amount from the associated transmission from the base station: 10 MHz in the case of the two bands in Table 2 (Figure 9).
- 35** Each frequency channel is 25 kHz wide so the 5 MHz band used by BT Airwave (see Table 2) contains 200 channels. The TETRA specification also allows the use of channels that are 12.5 kHz wide so that in principle the number of channels could be doubled.

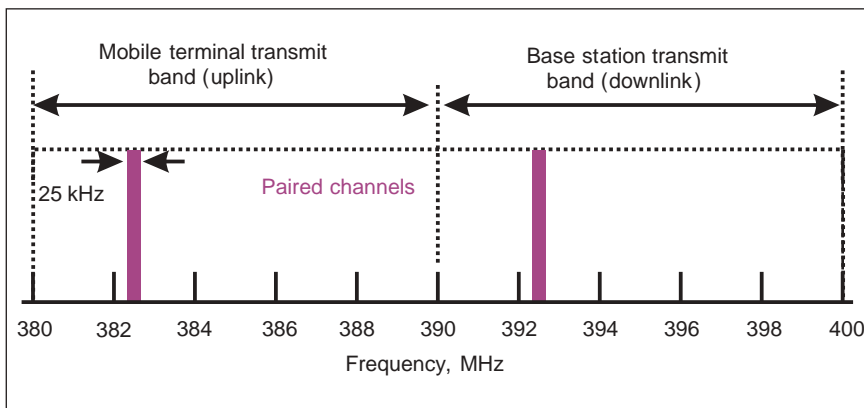


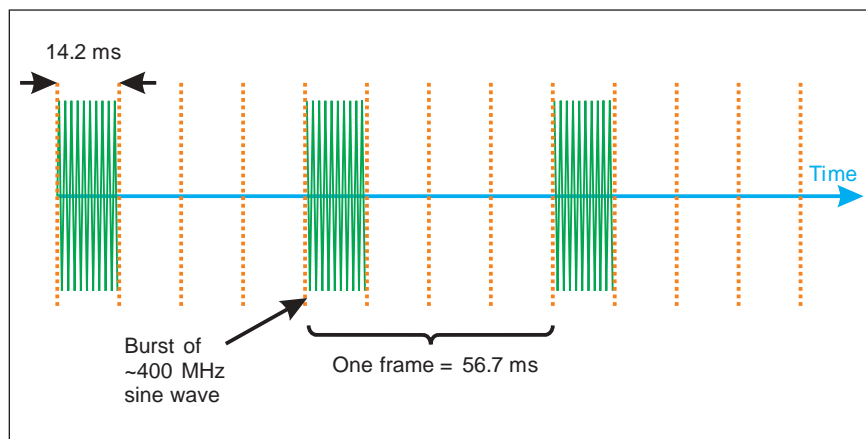
FIGURE 9 Paired
frequency channels
used by TETRA

Mobile terminals

Signal waveform

- 36** Signal information is carried by the radio signal from a TETRA hand portable or vehicle-mounted terminal using phase modulation (IEGMP, 2000). The resulting signal consists of a series of sine waves each lasting for $56 \mu\text{s}$. During each $56 \mu\text{s}$ period one of four possible phase changes occurs (-135° , -45° , $+45^\circ$ or $+135^\circ$), each one thus representing a pair of binary digits. The phase changes are accomplished by slightly varying the frequency of the signal.
- 37** For speech transmission, and allowing four users to communicate on the same frequency channel, the voice data are concentrated into *bursts* or *timeslots* 14.2 ms long which occur every 56.7 ms (the length of the *frame*). This corresponds to a duty factor of one-quarter and a pulse frequency of 17.6 Hz. The waveform is shown in Figure 10. However, for data transmission, including video, it is envisaged that more than one timeslot may be used. This would increase the duty factor and, if all four timeslots in the frame were used, the transmission would be continuous (duty factor of one). An increase in duty factor would lead to an increase in the average power and hence in the average exposure received by a user if the design and position of the hand portable were unchanged. Use of every other timeslot for transmission, so that two timeslots are used in every frame, would change the power modulation frequency to 35.2 Hz.
- 38** The discontinuous nature of the TETRA waveform is similar to that used by many other digital radio communications systems, including GSM (Global System for Mobile Communication) mobile phones. However, the TETRA timeslots last much longer than those of GSM and their pulse frequency is appreciably less. GSM uses 0.58 ms timeslots, which occur every 4.6 ms. This corresponds to a duty factor of one-eighth and a pulse frequency of 217 Hz. (It should be noted that pulse modulation also occurs at frequencies of 2.08 and 8.34 Hz with GSM.) More detailed information about the waveforms emitted by TETRA mobile terminals is given in the accompanying Technical Note.

FIGURE 10
Waveform from a
TETRA mobile
terminal



Maximum radiated power

- 39 The TETRA standard originally defined the four basic power classes shown in Table 3 for mobile terminals. The most recent edition of the standard includes four further sub-classes, designated 4L, 3L, 2L and 1L, that are each 2.5 dB lower in power than the four basic classes. Manufacturers can choose to produce and market products in accordance with any of these classes.
- 40 The BT Airwave network is designed to function with Class 3 (3 W) vehicle-mounted transmitters, and Class 4 (1 W) hand portables. However, users could choose to buy higher power terminals, such as 3 W hand portables or 10 W vehicle-mounted transmitters. Hand portables used with the Dolphin network are capable of transmitting only at a maximum output power of 1 W, while vehicle-mounted transmitters have the capability to transmit at 10 W, but are restricted to 3 W through signal information broadcast by the base stations.
- 41 The powers given in Table 3 are known as peak *output* powers and refer to the output power from the amplifier. The power radiated from the antenna depends on its efficiency and also on any losses in the cables connecting it to the amplifier. The radiated power will always be less than the output power and can be significantly less. The powers in Table 3 are referred to as *peak* because they represent the average output power over the duration of a burst.

Power class	Peak output power	
	dBm	watts
1	45	30
2	40	10
3	35	3
4	30	1

TABLE 3 Power classes for mobile terminals used with TETRA

Hand portables

- 42 Since the hand portable emission has a duty factor of one-quarter when used for speech, peak output powers of 1 W and 3 W correspond to average output powers (from the amplifier) of 0.25 W and 0.75 W, respectively. However, if more than one timeslot were used (data, video, etc), the average powers could rise to 1 W and 3 W, respectively. For GSM900 and GSM1800 mobile phones the peak output powers are 2 W and 1 W, respectively, and since the duty factor is one-eighth, the maximum average powers are 0.25 W and 0.125 W, respectively.
- 43 It is also of interest to compare these figures with the powers transmitted from the UHF analogue radios presently used by the police. For these, the peak output power is equal to 1.5 W and, since the transmission is continuous, the average power is also equal to 1.5 W. Since the frequencies are similar to those of TETRA, the efficiency of, for example, helical antennas used for analogue radios should be similar to that of helical antennas used for TETRA hand portables. Hence the maximum average *radiated* power from the two systems should scale approximately with their maximum average output powers.

- 44** In summary, the peak output power (1 W) of 1 W TETRA hand portables is less than or equal to those of GSM handsets (1 W and 2 W). However, the average power (0.25 W) is equal to or twice those of GSM handsets (0.125 W and 0.25 W). For 3 W TETRA hand portables, the peak and average powers are both greater than for GSM handsets. The peak output powers of 1 W and 3 W hand portables straddle those of the analogue radios currently in use while their average powers are both less than those of the analogue radios. These power data are summarised in Table 4 where, as in this paragraph, the average values are for one timeslot transmission.

TABLE 4 Peak and time-averaged output powers for various types of different hand-held radio terminals when operating at their maximum power level (the average figures for TETRA are for one timeslot)

System	Maximum output power (W)		APC available
	Peak	Average	
Analogue police radio (450–460 MHz)	1.5	1.5	–
TETRA Class 3 radio (380–385, 410–415 MHz)	3	0.75	✓ (not DMO)
TETRA Class 4 radio (380–385, 410–415 MHz)	1	0.25	✓ (not DMO)
GSM900 (890–915 MHz)	2	0.25	✓
GSM1800 (1710–1785 MHz)	1	0.125	✓

Vehicle-mounted terminals

- 45** The peak output powers of 3 W and 10 W used with vehicle-mounted terminals correspond to maximum average powers of 0.75 W and 2.5 W, respectively, which may be compared with the corresponding value of 20 W (both peak and mean) for the VHF analogue radio system currently in use.

Adaptive power control

- 46** In the most common mode of use (TMO) the network continually adjusts the power radiated by a TETRA mobile terminal to the minimum necessary to maintain radio contact during any given call. The peak output power is adjusted in steps of 5 dB between, for example in the case of a Class 4 terminal, the maximum peak power of 1 W (30 dBm) and a minimum peak power of 30 mW (15 dBm). As a consequence, the average power will also reduce in 5 dB steps. This technique of adaptive power control (APC) increases the battery life of a hand portable and is also used by GSM phones. It is not, however, used by TETRA mobile terminals in direct mode (DMO) nor by the analogue radios currently used by professionals such as the police. It should be noted that APC is not used if the signals from a mobile terminal pass to a base station through a repeater.

Base stations

- 47** The technical aspects of TETRA base stations that affect the exposure of people in the area around them have been discussed here. An earlier NRPB report (Mann *et al.*, 2000) gives background information about mobile phone base stations and explains much of the terminology that is used here.

Signal characteristics

48 TETRA base stations must be able to communicate with several hand portables at the same time and they differ from hand portables through their ability to transmit several different carrier frequencies simultaneously. The operation of Dolphin base stations is similar to that of GSM base stations in that only one carrier is transmitted from the antenna when there is no call traffic, but once call traffic starts, other carriers can be switched on. With BT Airwave the situation is somewhat different in that all possible carriers are transmitted continuously irrespective of the amount of call traffic. The maximum number of carriers that can be transmitted by a particular base station equals the number of transmitters that have been installed and this is normally no more than four.

49 The signals transmitted by TETRA base stations are phase modulated in a similar way to those from hand portables. However, since they transmit in all four timeslots, the transmission is continuous and not pulse modulated. More detailed information about the waveforms emitted by base stations is given in the accompanying Technical Note.

Radiated powers

50 Table 5 shows the power classes defined for base stations by the TETRA standard. Since the power needed to produce receivable signals increases with distance of the receiver from the base station, the choice of power class for a given base station is determined by the area to be covered.

Power class	Power	
	dBm	watts
1	46	40
2	44	25
3	42	16
4	40	10
5	38	6.3
6	36	4
7	34	2.5
8	32	1.6
9	30	1
10	28	0.6

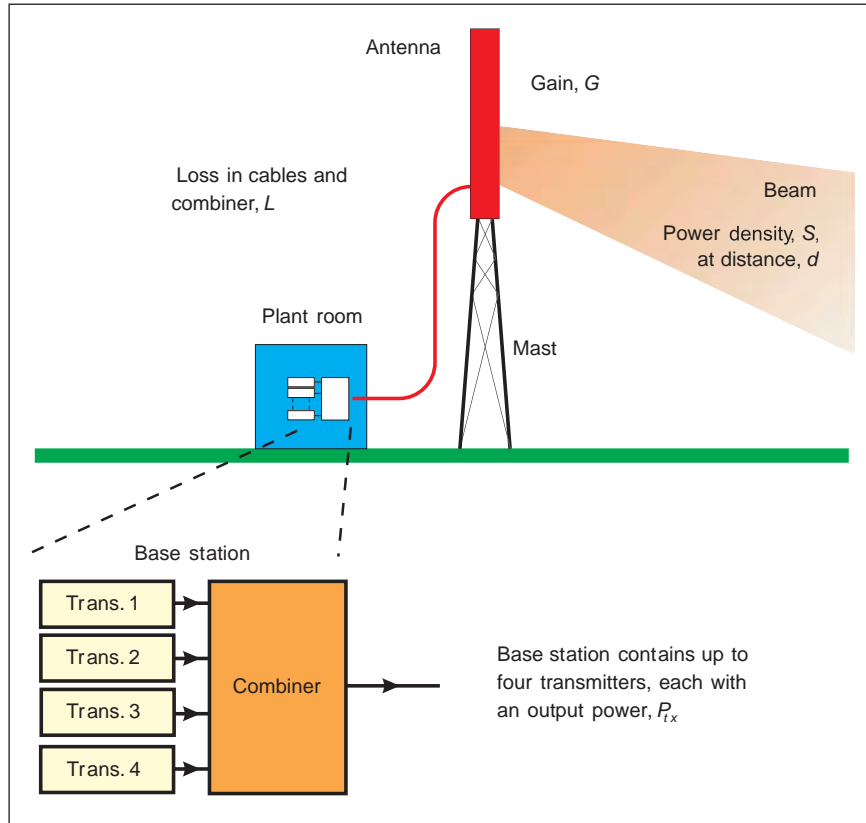
TABLE 5 Power classes for TETRA base stations

51 Table 5 refers to the power produced by a single transmitter at the base station's output connector which will be separated from the transmitter by the combiner, as shown in Figure 11.

52 Losses in the combiner and connecting cables reduce the total power radiated from the antenna to about one-third of the sum of the powers from the individual transmitters. So, for example, the maximum power radiated from the antenna used with a Class 2 base station (25 W from each of four transmitters) would be around 33 W.

53 The power directed into the beam from the antenna, which determines the power density, S , at a point in the beam that is sufficiently far away for the inverse square law

FIGURE 11 TETRA base stations contain up to four radio transmitters whose outputs are combined before being fed to an antenna and transmitted as radio waves



to apply (see paragraphs 70 and 71), is described by the effective isotropic radiated power (EIRP). This is the product of the total radiated power and the antenna gain. The licence awarded on 5 February 2001 to BT Airwave under the Wireless Telegraphy Act (1949, as amended) for the pilot stage does not specify a maximum EIRP, but requires it to avoid interference with other systems. The licence awarded to Dolphin specifies a maximum EIRP of 83 W (49.15 dBm), although this limit is similarly based on interference rather than health considerations.

Antenna characteristics

- 54** The base stations use both sector (usually around 120°) and omni-directional (360°) antennas depending on the requirements for coverage and capacity. Stacks of four folded dipole antennas are frequently used to achieve omni-directional coverage about an antenna site, such as the one shown in Figure 12. These antennas have gains in the range 6–12 (7.5–11 dB).
- 55** Typical sector antennas for TETRA have gains in the range 10–20 (10–13 dB) compared with gains of around 40–60 (16–18 dB) for GSM sector antennas. Since the gain of TETRA antennas tends to be lower than that of GSM antennas, the vertical beam widths are wider, eg 20° compared with 5° – 10° for GSM.

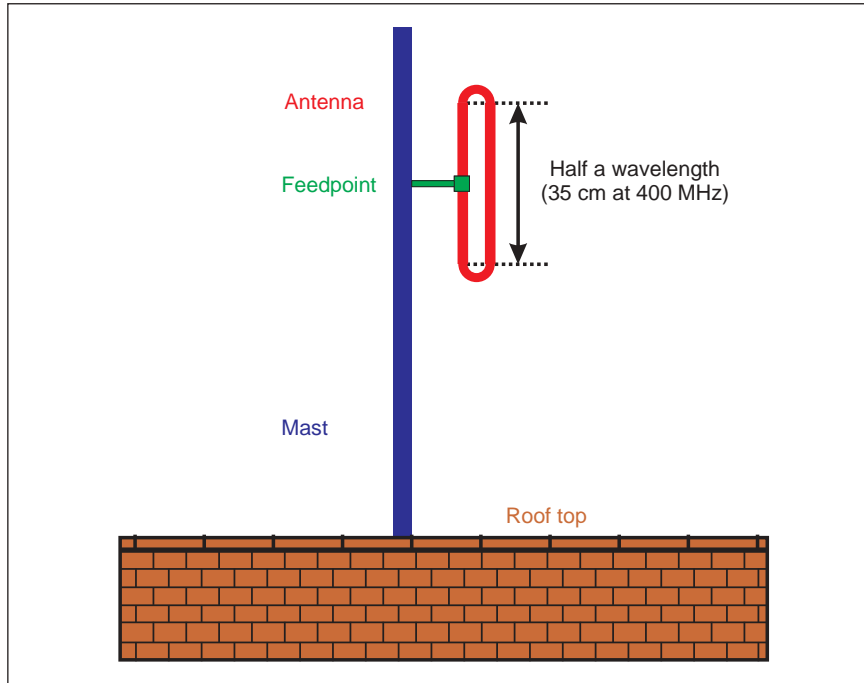


FIGURE 12 *Folded dipole antenna - vertical stacks of four dipoles on a metal pole are often used*

Acknowledgements

- 56 The Advisory Group would like to acknowledge the assistance of the operators of the UK-based TETRA networks for providing information used in the preparation of this section. In particular, thanks are due to Ray Mason of BT Airwave and Glyn Carter of Dolphin Telecom for acting as principal contacts through which rapid responses to detailed technical questions were obtained. The Advisory Group also wishes to thank David Barnfather of Lancashire Constabulary for providing photographs of TETRA installations.

EXPOSURE OF PEOPLE

- 57 The TETRA system will cause people's exposure to RF fields to be increased in a number of different ways but to a smaller extent than the same usage of the present analogue systems that they are designed to replace. Exposure to the RF fields from the various TETRA transmitters will be to those exposed in the course of their work, to other people at work and to the general public. Worker exposure arises predominantly from personal use of hand portables and from exposure to the fields from antennas mounted on the vehicles they occupy. Some workers may be exposed in the near vicinity of base station antennas. Public exposure will be for most of the time to environmental fields generated by the base stations and will occasionally be to fields from hand portables used by other people or fields from vehicle-mounted transmitters (either as passengers or as passers-by). Exposures of members of the public will generally be much lower than those of workers.

- 58** The exposure of the general public at normally accessible positions in the vicinity of TETRA base station transmitters would be expected to be small fractions of the exposure guidelines and will be comparable with the exposure arising from the operation of other telecommunication systems (Mann *et al*, 2000).
- 59** The exposure associated with the radio signals is normally expressed in terms of the specific energy absorption rate (SAR), which is a measure of the rate at which energy is absorbed from the field by tissue and is measured in watts per kilogram (W kg^{-1}). It is the quantity $\sigma E^2 / \rho$, where σ and ρ are, respectively, the electrical conductivity and the density of the tissue and E is the RMS value of the electric field strength at that point. The SAR varies from point to point in the body both because the electric field varies and also because the conductivity is different for different types of tissue. (The density is much the same for all tissues apart from bone.) Since the average values of the conductivity around 400 MHz and the density of the body are around 1.5 m^{-1} and 1000 kg m^{-3} , respectively, the typical RMS value of electric field strength needed to produce an SAR of 1 W kg^{-1} is about 30 V m^{-1} . (This is the electric field strength *inside* the body, which is always less than that at the surface.) SAR values for localised exposure of the head are normally quoted as averages over 10 g of tissue and over 6 minutes of exposure time since this is the form in which the relevant exposure guidelines specify basic restrictions (see the appendix).

Hand portables

- 60** Since the base station could be in any direction with respect to the user, the hand portable antennas are designed to radiate equally in all directions. This means that a proportion of the radiated power is directed towards and absorbed by the part of the user's body next to the hand portable, normally the head or the waist. When TETRA hand portables are held they are usually placed in one of three positions: next to one side of the face (left or right ear) like a mobile phone, or in front of the face like a walkie-talkie. These are called the normal use positions.
- 61** As a result of absorption by tissue, the strengths of the electric and magnetic fields inside the head fall approximately exponentially with the distance from that part of its surface that is nearest to the antenna of the hand portable. An indication of the rate of decay is given by the *skin depth*, which is the distance at which the field has fallen to a value equal to $1/e$ or 0.37 times that at the surface. Since the SAR is proportional to the square of the field strength, this falls in the same distance to $1/e^2$ or 0.14 of the surface value. The skin depth varies inversely with the square root of the frequency and is 2.5 cm for TETRA at 400 MHz and 1.7 cm for GSM at 900 MHz. Hence with TETRA, the energy is absorbed in a larger volume of tissue and so is less concentrated than with GSM. Consequently, near to the surface, a TETRA hand portable might be expected to produce a lower SAR than a GSM handset radiating the same power and held in the same position. However, since the radiation from TETRA penetrates further into the head, absorption from TETRA hand portables extends to distances greater than that from GSM handsets, although the SARs at these distances will be very much smaller than those near to the surface.
- 62** While these estimates give a useful indication of the way in which the energy is absorbed, more reliable values can be obtained by computer modelling of numerical phantoms or by measurements of the electric field strength and hence the SAR within

physical phantoms. The measurement procedure involves manipulating a small probe inside a hollow shell in the shape of the head. The shell is filled with a fluid whose electrical properties are similar to those of the average of the tissues inside the skull. The SAR is measured at many positions and the data are then used together with interpolation and extrapolation algorithms to obtain SAR values at points throughout the head.

- 63** Very little information exists on the SARs produced by TETRA hand portables. No numerical modelling appears to have been carried out. Measurements have been made of the SAR produced by two different commercially available TETRA hand portables, one with 1 W peak output power and the other with 3 W (Gabriel, 2000). The measurements were made for each of the three normal use positions and the results are shown in Table 6. The differences in the values for the left and right ear positions are most probably due to the fact that the antenna is not at the centre of the case of the hand portable.
- 64** The SARs in the table are values produced when the hand portable is transmitting at its maximum power. (The SAR will evidently be less if the power from the hand portable is less than the maximum because it has been reduced by adaptive power control.) For each position, the table shows the largest value at any measured point (spatial peak) together with the largest values obtained when averages are taken over volumes of mass 1 g or 10 g. It is seen that the values all comply with the NRPB guidelines and the ICNIRP occupational guidelines given in the appendix. Since, however, the SAR guideline values are averages over 6 minutes, calls lasting less than this will give rise to time-averaged SARs less than those in the table. Emergency service calls and other professional radio communications are likely to last much less than 6 minutes (the Advisory Group has been informed by the Home Office that trials indicate the average length to be around 40 s) so the SARs averaged over 6 minutes would usually be less than those in the table. It is important to emphasise though that several makes of hand portable are available and the SARs from these could each be larger or smaller than the values shown in the table; the largest and smallest SAR values reported for different GSM phones differ by a factor of five (K-tip, 2000).
- 65** Future developments in TETRA might require the use of more than one of the four timeslots in the frame; consequently, the SARs could be up to four times larger than those in Table 6, assuming the antenna would be mounted similarly in relation to the body. To meet the requirements of protection guidelines, careful thought would be required for the design of any such systems using 3 W power and with the antenna mounted close to the body. The Advisory Group has been advised, however, that when TETRA is used by the police for data transmission or video, the antenna is likely to be further from the body than when it is used for speech.

	SAR (W kg ⁻¹) for 1 W radio			SAR (W kg ⁻¹) for 3 W radio		
	Spatial peak	1 g averaged	10 g averaged	Spatial peak	1 g averaged	10 g averaged
Left ear	1.40	1.16	0.89	5.07	3.92	2.88
Right ear	1.72	0.94	0.88	5.07	2.74	2.33
Front	0.35	0.28	0.24	0.92	0.72	0.53

TABLE 6 Measured SARs produced in a phantom head exposed to radio signals from 1 W and 3 W TETRA hand portables

Remote speaker-microphones

- 66** The main exposure to the body is expected to be at waist level from the antenna and case of the hand portable and to be roughly comparable to that occurring in the head when the hand portable is held in one of the normal use positions, since the distance of the body from the antenna is similar. For the same reason, this should also be the case when a lightweight hands-free kit is used, although there could be some exposure from the earphone if RF current is induced in the cable. Future systems with an antenna attached to the speaker-microphone rather than to the hand portable will move the exposure from waist level to nearer the shoulder and head but the exposure could be less than in other positions since the antenna should be somewhat further from the body.

Vehicle-mounted terminals

- 67** The antenna is located outside the vehicle and, since its distance from the passengers inside the vehicle would normally be substantially greater than if they were using a hand portable, their exposure should be appreciably less even though the power is somewhat higher. The situation is complicated by the metal body of the vehicle. It is not evident that this could be relied upon to provide shielding since the non-conducting parts (eg windows) of the vehicle are comparable to the wavelength of the radiation (see Figure 12).

- 68** The exposure received by a user outside the vehicle reduces rapidly as the distance from the antenna increases. The fields around vehicle-mounted antennas should couple into the head in a similar way to those around the antennas used with hand portables because both types of antennas are essentially omni-directional and have little gain. Based on this assumption, the data in Table 6 suggest that, for both 3 W and 10 W vehicle-mounted terminals, the ICNIRP basic restrictions for the general public (ICNIRP, 1998) could be exceeded if a person's head were within a few centimetres of a vehicle-mounted transmitting antenna for several minutes. If more than one timeslot were used, the ICNIRP guidelines for occupational users could also be exceeded in similar circumstances.

Base stations

- 69** The maximum power radiated from TETRA base station transmitters is similar to that from mobile phone base station transmitters, ie a few tens of watts. At these power levels there will be regions in the immediate vicinity of the base station antennas where guidelines could be exceeded. Examples of calculations of power density in the vicinity of antennas are given below. Measurements made at locations of public access are also reported.

Near the antennas

- 70** As an example, NRPB has calculated the power density from an antenna consisting of a stack of four dipoles transmitting a total power of 33 W at a frequency of 425 MHz. Figure 13 compares the calculated power density with investigation/reference levels taken from the NRPB and ICNIRP guidelines (NRPB, 1993; ICNIRP, 1998).

- 71** From either measured or calculated data similar to those in Figure 13 it would be possible to derive a compliance boundary for a particular antenna. This is defined as the surface surrounding the antenna and at a distance from it at which the exposure equals the guideline level. Within the surface, guideline reference levels are exceeded while

outside they are not. Hence exposures can be controlled by restricting access to the *exclusion zone* - the zone within the compliance boundary. In the case of an omni-directional antenna, the compliance boundary is expected to be approximately cylindrical as shown in Figure 14.

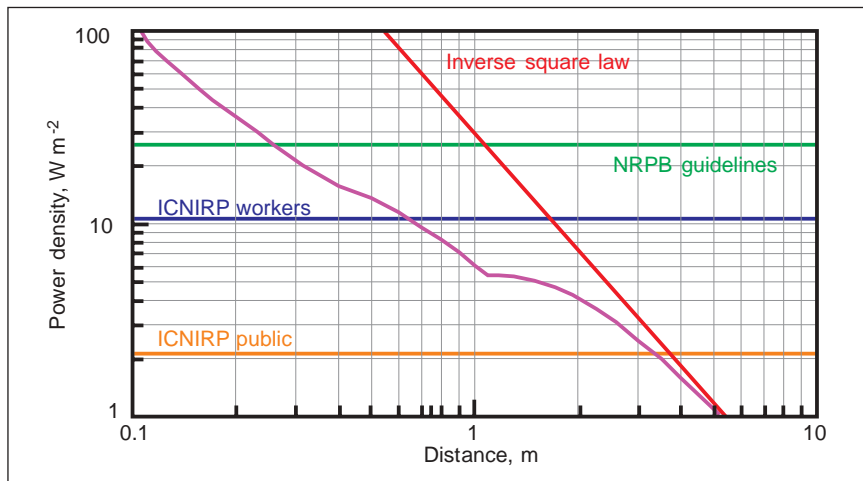


FIGURE 13 Plane-wave equivalent power density as a function of radial distance from a antenna consisting of a stack of four dipoles designed to give a gain of 11.5 (10.6 dB) and a radiated power of 33 W

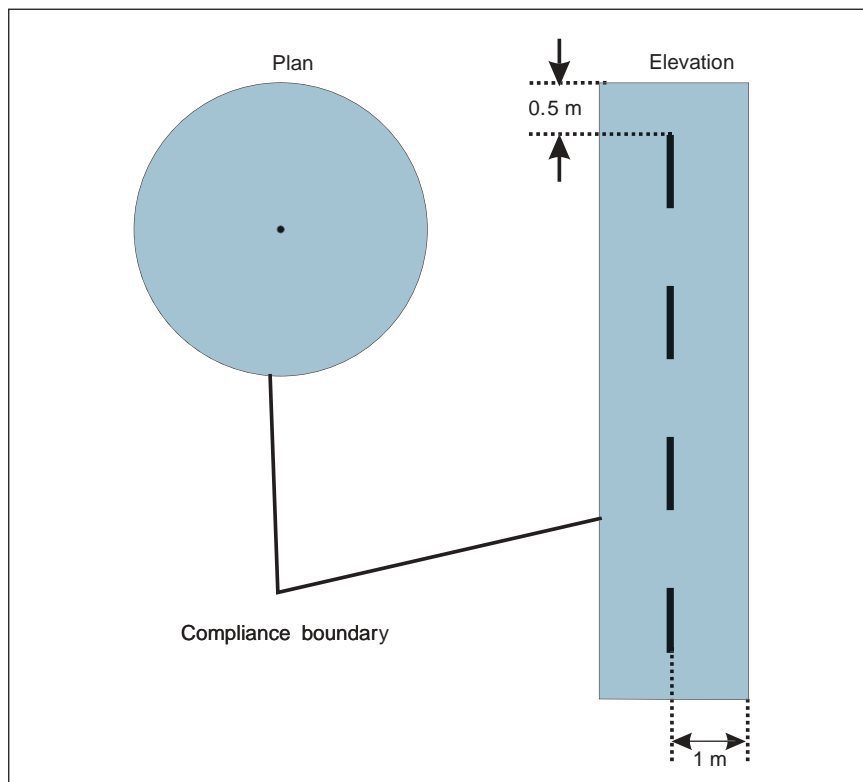


FIGURE 14 Example of a compliance boundary around an omni-directional TETRA base station antenna formed from a stack of four dipole elements

Ambient RF levels

72 Locations outside the exclusion zone, where the general public can be exposed, tend either to be beneath the main beam or within the beam but several tens of metres away. In both cases their exposure should be well below guideline levels (Figure 15).

73 NRPB has made measurements of the power density of radio signals at publicly accessible locations in the vicinity of several TETRA base stations. Examples are shown in Table 7 and exposures have always been small fractions of guidelines. The measurement at 42 m distance is higher than the measurement at 20 m because it is sufficiently far away for the main beam to be encountered at ground level.

FIGURE 15
Exposure of people near to base stations

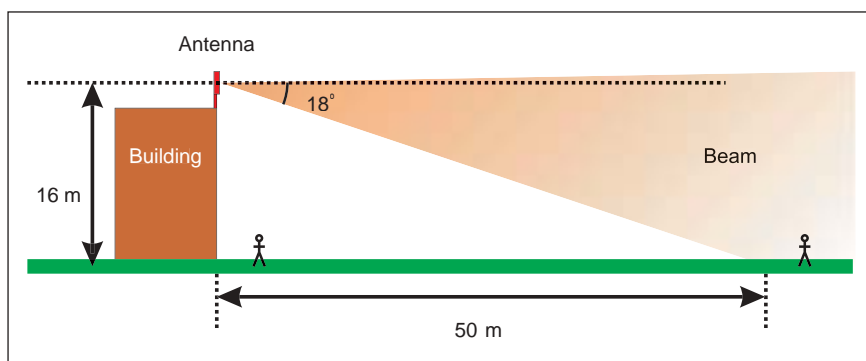


TABLE 7
A selection of indoor and outdoor measurements of power density representative of typical exposure from TETRA base station transmitters

Source antenna height (m)	Measurement position height (m)	Horizontal distance (m)	Line of sight	Indoor/ outdoor	Power density (mW m ⁻²)	% ICNIRP public reference level
16	1	42*	Yes	Outdoor	4.0	0.19
16	1	20†	Yes	Outdoor	0.47	0.0022
16	1	16	No	Indoor	0.028	0.00013
16	5	34	Yes	Indoor	0.62	0.0030
16	1	11	No	Indoor	0.025	0.00012
16	1	30	No	Indoor	0.159	0.00076

* Within main beam.
† Outside main beam.

Conclusions on exposure of people

74 Measurements of the maximum exposure from a 1 W TETRA hand portable used for speech transmission (one timeslot per frame) indicated an SAR below the ICNIRP basic restrictions for occupational and general public exposure. A similar measurement for a 3 W hand portable resulted in an SAR above the ICNIRP basic restrictions for the general public, but not for occupational exposures for which the system is designed. SAR values would increase if more than one timeslot were used and the hand portable were still held close to the body. They would remain below occupational guideline values with the 1 W hand portable, even if four timeslots per frame were used. However,

for the 3 W hand portable, the guideline values for occupational users would be approached or exceeded if three or four timeslots were used per frame.

- 75 The conclusions in paragraph 74 are for the particular make of hand portable on which measurements have been made. The SARs from other makes could differ and this could lead to different conclusions in relation to guidelines. However, the SARs given in Table 6 for a 1 W hand portable are so far below occupational guidelines that it seems unlikely that modification of the conclusions would be necessary for other makes when they are used for speech transmission.
- 76 No measurements appear to have been made of the exposures received inside or outside vehicles with externally mounted antennas (3 W or 10 W). However, the users inside a vehicle are normally appreciably further from the antenna than when they are using a hand portable and it seems unlikely that guidelines would be exceeded even if four timeslots per frame were used. The exposure received by a user outside the vehicle depends on their distance from the antenna. For both 3 W and 10 W vehicle-mounted terminals, the ICNIRP basic restrictions for the general public (ICNIRP, 1998) could be exceeded if a person's head were within a few centimetres of a vehicle-mounted transmitting antenna for several minutes. If more than one timeslot were used, the ICNIRP guidelines for occupational users could also be exceeded in similar circumstances.
- 77 The exposure values from base stations should be less than the ICNIRP guidelines for the general public if the exclusion zones are correctly set by the operators. The waveforms of the electromagnetic fields from base stations are continuous and are not pulse modulated as they are from mobile terminals.
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BIOLOGICAL EFFECTS OF AMPLITUDE-MODULATED RF FIELDS

- 78 The recommendation in the IEGMP Report that amplitude modulation of around 16 Hz should be avoided in future developments in signal coding was based on a limited body of scientific literature suggesting that RF fields, specifically when modulated at about 16 Hz, have certain effects on brain tissue (IEGMP, 2000). In 1975, Bawin *et al* claimed that exposure of pieces of chick brain (almost certainly containing few if any living cells) to modulated RF fields caused a small increase in the release of radio-labelled calcium ions ('calcium efflux'). Calcium plays an important role in many biological processes, especially in the function of nerve cells. Since this effect occurred at relatively low power, it was thought not to be due to heating. It remains the most extensively studied example of so-called 'non-thermal' effects. That initial study was followed by many others employing amplitude-modulated RF radiation.

Early studies

- 79 The first report in this area was from the laboratory of Professor Ross Adey at UCLA in the mid-1970s (Bawin *et al* 1975). These authors used techniques for measuring radiolabelled calcium ions in order to detect the outflow of calcium from large pieces of chick brain (isolated cerebral hemispheres). The fragments of brain were first incubated in a radioactive calcium solution to 'load' them with calcium. They were then put into a solution containing no radioactive calcium, and the subsequent level of radioactivity in the solution was taken as an indication of the movement of calcium ions from the brain. This movement was termed 'calcium efflux'.

- 80** There had been previous research on the passive (unstimulated) leakage of radiolabelled calcium out of (living) slices of guinea pig and rat brain. This work had shown that an initial rapid efflux (within 5–10 minutes), presumably from calcium in the extracellular space, was followed by slower exchange from ‘sheltered’ stores, presumably associated with non-nervous tissue, attached to membranes or inside nerve cells (Lolley, 1963; Cooke and Robinson, 1971; Bull and Trevor, 1972; Stahl and Swanson, 1972). Calcium efflux was enhanced by several minutes of electrical stimulation of the brain slice, using brief direct-current (DC) electrical pulses (Lolley, 1963; Bull and Trevor, 1972), and this was also true for the release of calcium from the surface of the cerebral cortex of the living (anaesthetised) cat brain (Kaczmarek and Adey, 1974). This might have resulted from the direct excitation of nerve cells by the electrical stimulation, causing them to fire impulses, since the change in intracellular potential during an impulse causes the opening of pores in the membrane, through which calcium can pass (voltage-activated calcium channels).
- 81** Adey’s group thought that, in the living animal, such calcium exchange might be associated with the small fluctuations in the potential across nerve cell membranes, of the type that can be detected with gross recording electrodes placed on the brain or even on the scalp (the electroencephalogram or EEG: see paragraph 111). They were trying to develop experimental methods to mimic the electrical changes of the EEG and decided to try stimulating the brain with RF fields, modulated in amplitude, rather than with DC pulses. They argued that such amplitude-modulated RF fields act directly on brain tissue, and might be expected to alter the calcium efflux, just like pulsed DC stimulation.
- 82** Bawin *et al* (1975) therefore decided to measure the efflux of calcium ions from isolated chick cerebral hemispheres exposed to modulated RF fields. They dissected the two hemispheres from new-born chicks and incubated them for 30 minutes in saline containing radioactive calcium ($^{45}\text{Ca}^{++}$). They were then put into chambers with fresh, non-radioactive saline at about 37 °C, and the efflux of $^{45}\text{Ca}^{++}$ was measured during exposure to RF fields of 147 MHz at moderate power density (10–20 W m⁻²). The field was either unmodulated (continuous wave) or sinusoidally modulated in amplitude at frequencies from 0.5 to 35 Hz. They found a statistically significant increase in efflux when the RF radiation was amplitude modulated at rates between 6 and 20 Hz, with most effect (19% increase) at 16 Hz. They suggested that the modulated RF fields produce electric fields within the brain, at the modulation frequency, and that these fields influence the EEG and cause a release of membrane-bound calcium (see Table 8).
- 83** This work was done before the widespread use of specific energy absorption rate (SAR) as an accepted measure of RF power absorption, and they described the intensities of exposure in terms of the external power density to which the tissue was exposed. The range of field strengths that they used, from 10–20 W m⁻², was unlikely to have produced significant heating in the brain tissue, even though there was, of course, no blood flow (which can efficiently remove heat from a warm part of the living body), and no special precautions were taken to avoid heating. The SARs have been estimated to have been about 0.002 W kg⁻¹ (Liddle and Blackman, 1984) and the rise in temperature was probably only about 0.001 °C. This result is often cited, then, as a ‘non-thermal’ effect of RF radiation.

Assay	Exposure	Response	Authors
Chick brain <i>in vitro</i>	147 MHz CW 0.5–35 Hz AM 10–20 W m ⁻² 0.002 W kg ⁻¹	Increase in efflux Maximum effect at 16 Hz AM No effect of carrier frequency alone	Bawin <i>et al</i> (1975)
Chick brain <i>in vitro</i>	450 MHz 16 Hz AM 7.5 W m ⁻²	Increase in efflux From extracellular sites	Bawin <i>et al</i> (1978)
Chick brain <i>in vitro</i>	147 or 50 MHz 3–50 Hz AM 3.7–43.2 W m ⁻² <0.075 W kg ⁻¹	Increase in efflux Maximum effect at 16 Hz AM Dependent on intensity not modulation	Blackman <i>et al</i> (1979, 1980a,b, 1985)
Chick brain <i>in vitro</i>	450 MHz 16 Hz AM	Increase in efflux Dependent on intensity	Sheppard <i>et al</i> (1979)
Human neuroblastoma cells	147 or 915 MHz CW 16 Hz AM	Increase in efflux Dependent on intensity and modulation	Dutta <i>et al</i> (1984, 1989)
Rat neuroblastoma cells	147 MHz 16 Hz AM	Enhanced acetylcholinesterase activity Dependent on intensity	Dutta <i>et al</i> (1992)
Synaptosomes	147, 450 or 450 MHz 16 Hz AM	Increase in efflux	Lin-Lui and Adey (1982)
Neurons of mouse medial habenular nucleus <i>in vivo</i>	2450 MHz 16 Hz AM	Reduction in the number of calcium- containing vesicles Increase in precipitation of calcium on surface of neurons	Kittel <i>et al</i> (1996)
Cat cortex <i>in vivo</i>	450 MHz 16 Hz AM	Irregular increase in efflux	Adey <i>et al</i> (1982)

TABLE 8 Calcium efflux studies using neural cells: positive results

AM = amplitude modulated, CW = continuous wave.

- 84** Bawin *et al* (1975) concluded that exposure to weak, modulated RF radiation might cause movement of the radiolabelled calcium ions out of nerve cells in the brain, especially for a modulation rate around 16 Hz. If positively charged calcium ions were to accumulate in the extracellular space around nerve cells, and to attach to nerve membranes, they might tend to 'stabilise' the membranes electrically and hence decrease nerve excitability (for instance, making it slightly harder to stimulate the nerve with an externally applied voltage). An increased calcium concentration around the membranes of a nerve might also alter the amount of calcium that subsequently enters the nerve in response to the passage of nerve impulses. Since such calcium entry regulates the release of neurotransmitter substances at nerve endings, a change in calcium levels might modify synaptic transmission between nerve fibres and other nerve cells. The limitations of this study are considered in paragraphs 94–101.

Subsequent *in vitro* studies

- 85** Essentially the same experimental approach was utilised in subsequent studies by Carl Blackman and colleagues at the US Environmental Protection Agency. Blackman *et al* (1979) exposed chick hemispheres to modulated 147 MHz fields at a range of intensities, estimated to have produced SARs less of than 0.075 W kg⁻¹. They found that efflux was significantly elevated at particular power densities, but not at lower or higher

intensities. Such behaviour (called a power density 'window') is very surprising on physical grounds, and the possibility of chance statistical variation must be considered (see Table 8).

- 86** Blackman *et al* (1980a,b) went on to use a number of different frequencies of amplitude modulation (3–30 Hz), two different RF carrier frequencies (147 and 50 MHz) and a range of power densities (between 3.7 and 43.2 W m⁻²). They also reported that calcium efflux was maximal around 16 Hz, but they found that the effects occurred in two power density windows, with no significant increase at about 20 W m⁻². The particular power densities for peak effects were different for the two carrier frequencies but the authors calculated that they corresponded to similar levels of energy absorption (SAR). Blackman *et al* (1985) went on to show that calcium efflux could be increased with 50 Hz amplitude modulation (of a 50 MHz carrier), but within different power density windows, again related to the SAR produced. They argued, then, that the effect on calcium efflux is not specifically related to the frequency of amplitude modulation but rather to the energy absorption produced.
- 87** The sequence of these papers led to the view – quite influential in the early 1980s – that RF modulation at or near 16 Hz might be especially effective in producing effects on biological systems. There followed a string of similar experimental studies, on a variety of different preparations. In some cases only 16 Hz modulated fields were used (on the assumption that the special effectiveness of this frequency of modulation had been indubitably established). Sheppard *et al* (1979) studied explants of chick brain and found an increase in calcium efflux with 450 MHz fields, modulated at 16 Hz, and they also reported a power density window. Dutta *et al* (1984, 1989), working on cultured human neuroblastoma (brain cancer) cells and Lin-Lui and Adey (1982), studying isolated fragments of the synaptic regions of nerve cells, also described an increase in calcium efflux. However, they employed only 16 Hz modulation, at 915, 147 and 450 MHz. Blackman *et al* (1989) also used only 16 Hz modulation (of a 50 MHz carrier), over a wide range of weak field strengths, and reported six different, very narrow power density windows.
- 88** In an attempt to identify the source of the released calcium, Bawin *et al* (1978) studied the effects of exposing chick brain tissue to 16 Hz amplitude-modulated 450 MHz radiation at 7.5 W m⁻² in saline containing various concentrations of (unlabelled) calcium or lanthanum, which is thought to alter calcium binding or transport across cell membranes. Although they confirmed the basic results on efflux, and suggested that it came from extracellular calcium binding sites, they were unable to draw firm conclusions about the nature of those sites.

Subsequent *in vivo* studies

- 89** All of this early work was done *in vitro* (and mostly on non-living material; see paragraphs 95–102), but there were a couple of 'positive' studies on living brain systems *in vivo*. More recently, Kittel *et al* (1996), using electron-microscopy to identify labelled calcium in a particular nucleus of the brain (the medial habenular nucleus), found that exposure of mice *in vivo* to 2450 MHz fields, amplitude-modulated at 16 Hz (no other conditions were tried), caused a reduction in the number of calcium-containing vesicles inside nerve cells and an increase in the amount of calcium precipitated on the surface of the cells. This implied that modulated RF causes calcium to move out of neurons,

which contradicts the earlier conclusion of Bawin *et al* (1978) that the efflux comes from extracellular binding sites.

- 90** Adey *et al* (1982) 'loaded' the surface layers of a region of the cerebral cortex with radioactive calcium in anaesthetised cats, by exposing it to saline containing radio-labelled calcium for 90 minutes. The bathing fluid was then replaced with radioactivity-free saline and the efflux of calcium was measured in samples of the fluid taken every 10 minutes. They found that exposure of the cortex to 450 MHz fields, amplitude modulated at 16 Hz (no other conditions were used), which they estimated to generate an RMS electric field strength of 33 V m^{-1} in the tissue, produced irregular increases in efflux.
- 91** More recently, Paulraj *et al* (1999) also reported an increase in calcium efflux (as well as increased levels of activity of the enzyme ornithine decarboxylase) in rat brain exposed *in vivo* for 35 days to 112 MHz fields of 10 W m^{-2} , modulated at 16 Hz.
- 92** There have been attempts to provide a theoretical account of the basis of these phenomena. Adey (1975, 1989, 1993) suggested that changes in calcium efflux could be due to an amplification process in which weak electric fields, set up in the tissue at the extremely low frequency of amplitude modulation, might act as a 'trigger' for the initiation of long-range co-operative events within the cell membrane. Blackman *et al* (1989) also speculated that their multiple power density windows might be related to some influence of the RF field on the microviscosity of cell membranes, tiny effects becoming amplified. More comprehensive physical models have been offered, based on interaction between calcium ions and protein binding sites in the membrane (eg Chiabrera *et al*, 2000, and Thompson *et al*, 2000), but have not gained general acceptance.
- 93** There is, then, still no accepted theoretical basis for the effect of modulated RF fields on calcium efflux. This would seem to require the presence of a non-linear mechanism operating on the time-scale of the carrier frequency, capable of 'demodulating' the amplitude-modulated component and hence generating oscillating currents at the extremely low frequency (ELF) of the amplitude modulation. Even weak ELF currents are known to influence the excitability of nerve cells and the movement of ions across their membranes (see Jefferys, 1995). It appears unlikely that biological membranes could provide a non-linear mechanism capable of converting the modulating frequency into an ELF current (IEGMP, 2000), but it is possible that other elements of the cells may serve as non-linear, demodulating components.
- 94** Joines and Blackman (1980), Joines *et al* (1981) and Blackman *et al* (1981) have offered a mathematical model through which they calculated the electric fields produced in the isolated chick hemisphere by exposure to RF radiation. They concluded that the extent of calcium efflux depends on the electric field strength within the tissue (and hence SAR), regardless of the carrier frequency, and to some extent independent of the particular frequency of amplitude modulation.

Criticisms and failures to corroborate the findings

- 95** There are many points of concern and contention regarding the design and performance of the original study. Calcium efflux was not, and is not, a standard, widely-employed measure of nerve function: any change in efflux is difficult to interpret, and carries no immediately obvious health risk. More significantly, most if not all of the cells in large brain explants, such as the whole cerebral hemispheres used, would have been

dead within minutes of removal from the animal. One of the most puzzling aspects of this result is the lack of a theoretical explanation. If it genuinely occurs without any tissue heating, it is difficult to understand what kind of interaction between RF radiation and tissues could be responsible. The IEGMP Report (2000) considered a number of possible physical interactions that have been suggested as a basis of 'non-thermal' effects (protein unfolding, polarisation of cells, rectification by cell membranes and 'resonant' interactions), but IEGMP was unconvinced by any of them. Similar conclusions were reached by the Expert Panel Report of the Royal Society of Canada (1999), and the Report from the French Ministry of Health (Zmirou, 2001).

- 96** Calcium efflux from brain explants almost certainly involves a number of factors, including the release of calcium bound to or adherent to membranes or simply trapped in the interstices of the tissue. These processes are likely to be influenced by temperature.
- 97** In agreement with the above, the design and interpretation of the early studies on calcium efflux from chick brain hemispheres have been criticised by Myers and Ross (1981) and Blackwell and Saunders (1986), and in a number of other papers and reports. Particular concern has been expressed about the status of the tissue, and therefore the significance of the results. As mentioned above, in large pieces of brain, such as chick hemispheres, maintained in unoxygenated fluid, most if not all of the nerve cells would have died very quickly. Indeed, Bawin *et al* (1975) showed that the effects of RF exposure on calcium efflux persisted in the presence of the metabolic poison, sodium cyanide.
- 98** The methods of analysis have also been criticised. In the Bawin *et al* (1975) experiments, the 'control' (unstimulated) measurements were pooled and normalised for comparison with the values during exposure, hence masking any variation in the unstimulated levels of efflux. Myers and Ross (1981) also criticised the work of Blackman *et al* (1979, 1980a,b) on the grounds that variation in the data from the control samples, rather than genuine fluctuations in the stimulated efflux, could have generated the apparent power density windows.
- 99** Bawin and Adey (1976, 1977) found that exposure of pieces of chick or cat brain to extremely low frequency fields of 6 or 16 Hz (without an RF 'carrier' signal) produced a significant decrease in calcium efflux over a particular power density window. Although this study did not employ RF fields, it is still puzzling, since it directly contradicts not only subsequent work by Blackman *et al* (1982), but also earlier findings of Kaszmarek and Adey (1974) on the EEG (see paragraphs 111–116), which had provided the rationale for the original study with RF fields by Bawin *et al* (1975). Despite the attempt by Blackman *et al* (1991) to explain these discrepancies in terms of temperature differences, the contradiction is still unresolved.
- 100** Moreover, since the early 1980s, a number of studies, using a variety of preparations and exposure conditions, and generally quite rigorously designed, have failed to detect an increase of calcium efflux from tissues as a result of RF exposure (see Table 9).
- 101** Albert *et al* (1987) essentially repeated the original Bawin *et al* (1975) experiment and found no increase in calcium efflux from either isolated chick brain hemispheres or oxygenated slices of chick cortical tissue, exposed for 20 minutes to 147 MHz fields, modulated at 16 Hz (7.5 W m^{-2}). Shelton and Merritt (1981) found no effect on calcium efflux from fragments of rat brain. They used 1000 MHz radiation, pulsed at 16 or 32 pulses per second, for 20 minutes, up to quite high time-averaged power densities ($5\text{--}150 \text{ W m}^{-2}$). Merritt *et al* (1982) went on to describe similar negative results for rat

brain, loaded with calcium by intraventricular injection *in vivo* and exposed *in vitro* or *in vivo* to RF fields of 1000, 2060 and 2450 MHz, pulsed at a variety of frequencies including 16 Hz.

- 102** The UNEP/WHO/IRPA Report (1993), which reviewed this field quite extensively, came to the conclusion that the original observation was not reliably established and that there was no strong reason to believe that 16 Hz modulation has special effects.

Assay	Exposure	Response	Authors
Chick cerebral hemispheres <i>in vitro</i>	147 MHz 16 Hz AM for 20 min 7.5 W m ⁻²	No effect on efflux	Albert <i>et al</i> (1987)
Rat brain <i>in vitro</i>	1000 MHz pulsed 10 or 20 ms pulses 16 or 32 pps for 20 min 5-150 W m ⁻²	No effect on efflux	Shelton and Merritt (1981)
Rat brain loaded with calcium <i>in vivo</i> , exposed <i>in vivo</i> or <i>in vitro</i>	1000, 2060 or 2450 MHz pulsed or 2060 MHz CW 10 ms pulses at 8, 16 or 32 pps for 20 min 0.12-2.9 W kg ⁻¹	No effect on efflux	Merritt <i>et al</i> (1982)

TABLE 9 Calcium efflux studies using neural cells: negative results

AM = amplitude modulated, CW = continuous wave; pps = pulses per second.

Studies of non-neural cells

- 103** Albert *et al* (1980) reported a small increase in calcium efflux from slices of rat pancreas exposed to weak 147 MHz fields amplitude modulated at 16 Hz. However, when they 'loaded' the slices with radioactive leucine (an amino acid which would have incorporated into proteins of the type secreted by pancreatic cells), the RF field did not cause an increase in the release of radioactivity. Since the secretory process depends on the level of calcium inside cells, they concluded that the calcium efflux elicited by RF stimulation does not affect intracellular calcium. As the release of neurotransmitters from nerve terminals also involves calcium-dependent secretion, this finding suggests that even if the efflux of calcium from the brain is a genuine phenomenon, it is unlikely to interfere with synaptic transmission (see Table 10).
- 104** Schwartz *et al* (1990) measured the efflux of calcium from isolated, living frog hearts, exposed to 240 MHz fields, at very low SARs, from 0.15-3 mW kg⁻¹. They found no increase with continuous-wave fields, nor with fields modulated at 0.5 Hz (close to the beating frequency of the heart). For fields modulated at 16 Hz, there was an increase (by about 20%) at 0.15 and 0.3 mW kg⁻¹, but not at any of the four other exposures tested. They concluded that 16 Hz modulated RF fields might affect calcium efflux in heart tissue over restricted power density windows, as reported for neural tissue. However, the fact that only two out of a large number of conditions produced effects that were only just statistically significant ($p < 0.05$) raised the possibility that they were due to chance variation. Indeed, Schwartz and Mealing (1993) subsequently examined the effects of 1000 MHz fields (producing SARs up to 1.6 W kg⁻¹) on calcium efflux and contractile force of isolated strips of frog heart muscle and found no reliable effects, with either unmodulated RF or amplitude modulation at 0.5 or 16 Hz.

TABLE 10 Calcium efflux studies using non-neural cells

Assay	Exposure	Response	Authors
Rat pancreas slices <i>in vitro</i>	147 MHz 16 Hz AM	Small increase in efflux Intracellular calcium not affected	Albert <i>et al</i> (1980)
Whole frog heart	240 MHz CW 16 Hz AM	Increase in efflux Dependent on intensity	Schwartz <i>et al</i> (1990)
Isolated strips of frog heart muscle	1000 MHz CW 0.5 or 16 Hz AM up to 1.6 W kg ⁻¹	No effect on efflux	Schwartz and Mealing (1993)
Mouse spleen <i>in vitro</i>	147 MHz 9, 16 or 60 Hz AM 1.1 to 4.8 W m ⁻²	No effect on B-lymphocyte antigen-antibody capping	Sultan <i>et al</i> (1983)
Mouse T-lymphocytes <i>in vitro</i>	450 MHz 0-100 Hz AM 15 W m ⁻²	Transient suppression of cytotoxicity Maximum at 60Hz Dependent on modulation	Lyle <i>et al</i> (1983)
Human tonsil lymphocytes <i>in vitro</i>	450 MHz, 3 or 100 Hz AM 10 W m ⁻²	Transient decrease in non-cAMP-dependent protein kinase activity No effect on cAMP-dependent activity	Byus <i>et al</i> (1984)
Human mononuclear lymphocytes <i>in vitro</i>	2450 MHz pulsed 16 or 50 pps up to 4 W kg ⁻¹	No effect on cell viability, or DNA and total protein synthesis	Roberts <i>et al</i> (1984)

AM = amplitude modulated, CW = continuous wave; pps = pulses per second.

- 105** There have been several studies of possible non-thermal effects of RF exposure on isolated components of the immune system, some of which have specifically addressed the issue of amplitude-modulated or pulsed signals. Lyle *et al* (1983) assessed the ability of cultured T-lymphocytes from the mouse to kill foreign cells by measuring the amount of a radioactive tracer material (⁵¹Cr) released from the target cells during incubation with the T-lymphocytes. They reported that T-cell killing was suppressed during exposure to modulated 450 MHz at a power density of 15 W m⁻². The greatest suppression (20%) occurred at a modulation frequency of 60 Hz with smaller effects at 16, 40, 80 and 100 Hz. Since the unmodulated carrier wave at the same power density did not affect T-cell killing, the authors attributed the suppressive effects to modulation of the RF field. However, other workers have been unable to identify similar effects. Sultan *et al* (1983) examined the influence of 147 MHz radiation, sinusoidally modulated at 9, 16, or 60 Hz, on B-lymphocyte capping (another measure of the immune system) in mouse spleen lymphocytes. Power densities ranged between 1.1 and 4.8 W m⁻². No statistically significant differences in capping were observed between the exposed and control samples at any of the modulation frequencies and power densities employed, as long as both preparations were maintained at the same temperature. Roberts *et al* (1984) exposed isolated human mononuclear lymphocytes to 2450 MHz pulse modulated at 16 or 60 Hz and at SARs of up to 4 W kg⁻¹ and found no effect on viability or on unstimulated or mitogen-stimulated DNA synthesis or total protein synthesis.

Possible biological consequences of calcium efflux

- 106** If exposure to RF fields does induce changes in calcium ion movement in neurons and other cells, then these changes would be expected to influence other measures of nervous system function. A few studies have investigated these possibilities.

Neuronal excitability

- 107** In view of the reports on increased calcium efflux, which might be expected to lead to a decrease in the excitability of neurons, Arber and Lin (1984, 1985) investigated the effects of RF exposure on the biophysical properties of nerve cells in the snail (*Helix aspersa*). They did indeed report an increase in membrane conductance and a decrease in the spontaneous firing of impulses after exposure for an hour to continuous-wave 2450 MHz radiation. The effects were abolished by the application of EDTA, which binds calcium. When the RF field was 'noise modulated' (varying in amplitude randomly over a range from 2 Hz to 20 kHz), the effects were said to be more variable, but sometimes there was a decrease in conductance and bursts of impulses. However, these effects occurred only at a high RF intensity (SAR of 6.8 or 14.4 W kg⁻¹), and temperatures less than body temperature (generally 8 or 21 °C).
- 108** McRee and Wachtel (1980) described an irreversible reduction in the amplitude of nerve impulses and a decrease in the excitability of the frog sciatic nerve after exposure for more than 20 minutes to continuous-wave 2450 MHz radiation, but again only at quite high levels (SARs equal to or greater than 10 W kg⁻¹). In 1982, McRee and Wachtel described similar reductions in nerve excitability using intense pulsed microwaves (10 µs pulses at 50 pulses per second; average SAR 10 W kg⁻¹). Wachtel *et al* (1975) and Seaman and Wachtel (1978) described a decrease in spontaneous impulse activity of neurons isolated from the marine gastropod *Aplysia*, but also only at relatively high RF field strengths.
- 109** In the context of TETRA, it is important to note that these claimed changes in nerve excitability were not enhanced by amplitude modulation or pulsing. They also occurred only with relatively high levels of RF fields. Although some of these studies attempted to control temperature, or demonstrated that the effects could not be mimicked by imposed temperatures, there remains the possibility that they were due to local temperature changes. For example, Courtney *et al* (1975) saw no electrophysiological changes in the rabbit superior cervical ganglion exposed to 2450 MHz (continuous-wave), even up to SARs of 1000 W kg⁻¹, under temperature-controlled conditions. Chou and Guy (1978) also reported no change in excitability of frog sciatic nerve at modest intensities. They did see a slight increase in conduction velocity with more intense RF and this was almost certainly dependent on the temperature rise, since it could be mimicked by a 1 °C rise in temperature. Wang *et al* (1991) used sensitive patch-clamp recording methods to study dorsal root ganglion cells (the cell bodies of sensory nerve fibres) *in vitro*, and found no change in the membrane resting potential or its electrical capacitance, nor in the characteristics of impulses during exposure to continuous-wave 2450 MHz radiation under temperature-controlled conditions. Linz *et al* (1999), who also employed whole-cell patch-clamping, found no effect of low intensity continuous or pulsed RF fields on the membrane potential, action potentials or calcium and potassium currents of isolated heart muscle cells.
- 110** More recently, however, Tattersall *et al* (2001) have reported that exposure for 15 minutes of rat hippocampus tissue 'slices' *in vitro* to 700 MHz continuous-wave RF radiation at SARs estimated to lie between only 0.0016 and 0.0044 W kg⁻¹ modulated the excitability of exposed nerve tissue. These changes in neuron excitability were assessed from measurements of changes in the height of the 'population spike', the synchronous discharge of a number of neurons triggered by an external electrical

stimulus. At low field intensities, the predominant effect was a potentiation of the amplitude of the population spike by up to 20%, but higher intensities could produce either increases or decreases of up to 120% and 80%, respectively. These effects could not be simulated by imposed temperature changes of up to 1 °C, suggesting that exposure to low level RF radiation can modify neuronal excitability and therefore perhaps affect other aspects of brain function. In the context of TETRA, however, it must be emphasised that the fields used in this study were not modulated or pulsed. It is difficult, then, to link them to the reports on calcium efflux specifically produced by amplitude-modulated fields.

Brain waves

- 111** The electroencephalogram (EEG) is a 'gross' electrical signal recorded from the cerebral cortex with electrodes placed in close contact with the scalp or the brain itself. The signal consists of small fluctuations in voltage, with frequencies ranging from about 1 to 60 Hz. There are clear changes in the frequency composition of the EEG in different states of sleep (low frequencies dominant), arousal and attention (high frequencies dominant). The EEG can be 'driven' by direct electrical stimulation at particular extremely low frequencies in various parts of the brain. Animals can, for instance, be made to go to sleep, by stimulation at about 8 Hz in several parts of the brainstem or the cerebral cortex, and to wake up if the same or other brain regions are stimulated at higher frequencies.
- 112** The carrier frequencies of RF fields are many orders of magnitude higher than the frequencies in the EEG and the maximum impulse frequency of individual neurons. Nerve membranes are essentially 'transparent' to RF fields (Montaigne and Pickard, 1984; Adair, 1994). It is therefore very unlikely that RF fields could have a direct electrical influence on the potential across nerve membranes. Equally, it seems implausible that any low frequency modulation (AM or pulses) imposed on an RF carrier could produce electrical fluctuations in nerve cells. However, there might be some other non-linear element within neuronal cell bodies capable of converting the modulating frequency into a flow of current, which might affect the excitability of neurons. In consequence of the close relationship between the rhythm of the EEG and the behavioural state, there has been considerable interest in the possibility that exposure to low levels of pulsed or modulated RF radiation might alter the EEG.
- 113** In 1967, Baranski and Edelwejn reported that exposure to fairly intense (130–140 V m⁻¹) 2950 MHz microwave radiation, amplitude modulated at the high rate of 1200 Hz, increased the amount of low frequency activity in the EEG. Before their original study of calcium efflux, Bawin *et al* (1973, 1974) used Pavlovian conditioning methods to train cats to produce particular EEG rhythms in response to a light flash, and then exposed them to RF fields (147 MHz) of low power density (10 W m⁻² or less), modulated in amplitude at frequencies between 1 and 25 Hz. They reported changes in the EEG pattern and in various other behavioural parameters, including the rate of performance of the task. They argued that such amplitude-modulated RF fields act directly on brain tissue, and they predicted that such fields might alter calcium efflux, just like pulsed DC stimulation.
- 114** Servantie *et al* (1975) reported an increase in low frequency activity in the EEG of rats exposed to 3000 MHz microwaves of fairly high field strengths (130–140 V m⁻¹)

pulsed at 500–600 pulses per second. Shandala *et al* (1979) also described subtle effects on the EEG in rats and rabbits exposed to RF fields of 2375 MHz. However, the radiation was not amplitude modulated or pulsed; it was very prolonged (7 hours per day for 30 days); and it was fairly high in field strength. Thuroczy *et al* (1994) found changes in the spectral composition of the EEG in rats, but they occurred for continuous-wave RF fields as well as at 16 Hz amplitude-modulated fields, and the field strengths were very high. Takashima *et al* (1979) also reported that prolonged exposure (2 hours per day for 6 weeks) of rabbits to strong 1–10 MHz field strengths, modulated at 15 Hz, resulted in an increase in the low frequency component of the EEG. However, 'acute' exposure (for 2 hours) had no obvious effect, even at high field strength.

115 Experiments were carried out by Rosenstein of the US Environmental Protection Agency (reported by McRee *et al*, 1979), in which rats were exposed to continuous-wave RF fields (425 or 2450 MHz) from late fetal life until adulthood. He saw no changes in either the spontaneous EEG or the electrical responses evoked by flashes of light (visual evoked responses). Mitchell *et al* (1989) reported the findings of a joint project on this subject carried out in the USA and the former Soviet Union. Both groups exposed rats to fairly intense continuous-wave RF fields for 7 hours. Interestingly, both teams found small but just statistically significant reductions of power in the EEG, but in different parts of the frequency spectrum.

116 There have also been a number of studies of the EEG in human volunteers, most of them using simulated mobile phone signals (therefore not directly relevant to TETRA). Some of them have described subtle changes in the spontaneous EEG (Reiser *et al*, 1995), the EEG during sleep (Mann and Roschke, 1996; Borbely *et al*, 1999) and the EEG signals recorded in response to sensory stimuli (Eulitz *et al*, 1998; Freude *et al*, 1998; Krause *et al*, 2000). However, others have failed to detect any such effects (Roschke and Mann, 1997; Urban *et al*, 1998; Wagner *et al*, 1998). There is currently no evidence that low frequency modulated fields are of special significance, and therefore the relevance of this work to TETRA is uncertain. However, this subject certainly deserves more research.

Epilepsy

117 One particular concern that has been voiced publicly, through the media, is that pulsed fields might 'drive' brain rhythms and hence precipitate epileptic seizures in prone individuals. It is important to consider this possibility, but it seems unlikely on the basis of both theory and evidence. As explained above, nerve membranes are thought to be essentially electrically 'transparent' to RF radiation, and therefore the impulse activity of nerves ought not to be altered by such fields. However, a comparison has been made with the fact that even quite low intensity light (which is electromagnetic radiation of even higher frequency), pulsed at low rates (around 15 Hz), can trigger fits in humans and animals who suffer from 'photic epilepsy'.

118 The comparison with photic epilepsy is not as valid as it might seem. Obviously, light affects the eye, which very efficiently converts it into nerve impulses, which are transmitted to the brain. Photoreceptors in the eye can detect very dim light and produce signals in response to it. Hence, even dim flashing light gives rise to bursts of impulses at the same frequency in the optic nerve, which can trigger epileptic discharges in the brain of sensitive individuals. However, there is no known mechanism

that could convert pulsed RF fields into synchronised bursts of impulses: there is no equivalent to the eye for RF radiation. On the basis of existing knowledge, the analogy of photic epilepsy seems unjustified.

- 119** Recently, however, Tattersall *et al* (2001) have shown that unmodulated RF fields of 700 MHz actually reduced or abolished epileptiform bursting of groups of neurons induced by application of the drug 4-aminopyridine to slices of rat hippocampus. Although this obviously gives no reason to think that RF exposure is likely to trigger epileptic seizures, it does suggest that RF fields can alter the general excitability of neural networks, presumably by shifting the intracellular potential of neurons. This again raises questions about how an electric field oscillating at a frequency much faster than the response time of the ion gates in the membrane can establish a potential across the membrane. There does remain, however, the possibility that some other molecular elements within the cell might have non-linear properties, capable of producing potential shifts.

Other possible biological effects

- 120** IEGMP (2000) described evidence for a variety of other biological effects of RF fields (in most cases not amplitude modulated), including decreased motor activity, changes in learned behaviour, leakiness of the 'blood-brain barrier', damage to the eye, changes in the activity of enzymes and the expression of genes, shrinkage of cell nuclei, decrease in fertility, and promotion of cancer in cancer-prone mice (see Krewski *et al* 2001, for a recent update). However, many effects occurred only at high intensities, and are therefore likely to have been caused by heating. Other positive results at low intensities have been contradicted by negative studies and must therefore be considered controversial.
- 121** In any case, there is no indication that these other claimed 'non-thermal' effects occur selectively with 16 Hz amplitude- or pulse-modulated fields. Therefore these other results are not specifically relevant to TETRA.

Epidemiology

- 122** No epidemiological study as yet has explored the risks associated with telecommunications systems such as TETRA which use RF radiation modulated at frequencies around 16 Hz. There are, however, published reports relating to other forms of RF radiation, including some in which the carrier signal is modulated at other frequencies. These investigations have focused on people using mobile phones, people exposed to RF radiation through work or hobbies (eg amateur radio operators), and people living near radio and television transmitters. Most of the studies have addressed potential risks of cancer (especially brain tumours, leukaemia and lymphoma), but some have examined mortality from other causes, possible adverse effects on pregnancy, and suspected short-term effects of using mobile phones such as headache and difficulty in concentration.
- 123** The research that had been published before April 2000 was reviewed by IEGMP (2000). In brief, IEGMP concluded that there is strong evidence that engaging in a mobile phone conversation while driving impairs driving performance. No persuasive evidence was found, however, that exposure to RF radiation in general - or, to the limited extent that it has been investigated, mobile-phone-related exposures in particular - causes

disease in people. It was noted that a substantial number of people who use phones report symptoms such as fatigue, headache, and feelings of warmth behind the ear that occur during or shortly after phone use, but it unclear to what extent, if any, these symptoms are caused by RF radiation.

- 124** Since the IEGMP Report was finalised, three further studies, from the USA and Denmark, have been published on the risks of cancer in relation to use of mobile phones. The Advisory Group is aware that a fourth, from Sweden, has recently been publicised in the media, but as far as is known it has not yet been published in any peer-reviewed journal, and therefore it is unavailable for scientific scrutiny.
- 125** The first (Muscat *et al*, 2000) was carried out in the USA, and compared the use of mobile phones in 469 people with brain cancer and 422 matched controls. No overall association was found between brain cancer and use of mobile phones (as would be expected given the rapid expansion of the technology during the 1990s, most use had been fairly recent in both cases and controls). The authors noted that most exposure would have been to analogue rather than digital signals.
- 126** The second study (Inskip *et al*, 2001) was also conducted in the USA, and again used a case-control design. It included 782 cases (489 with glioma, 197 with meningioma and 96 with acoustic neuroma) and 799 controls (patients admitted to hospital with various non-malignant conditions). The mobile phones used by the people in the study were mostly analogue, with the main use being in the early- to mid-1990s. In comparison with never or very rarely having used a cellular phone, the relative risks (RR) associated with cumulative use of more than 100 hours were estimated as 0.9 for glioma and 0.7 for meningioma. There was a small elevation of risk for acoustic neuroma, but this could easily have occurred by chance (RR 1.4, 95% confidence interval (CI) 0.6–3.5). There was no evidence of higher risks with heavier or more prolonged use of mobile phones.
- 127** The third investigation was carried out in Denmark (Johansen *et al*, 2001), and examined cancer incidence among more than 400 000 users of cellular phones during 1982–95, who were identified from the subscriber lists of two operating companies. Subjects were followed to the end of 1996 through the Danish Cancer Registry. Overall, the number of cancers observed in the cohort was less than would have been expected from rates in the national population (3391 versus 3825), with deficits in particular for lung cancer and other smoking-related tumours. No excesses were found for cancers of the brain or nervous system (standardised incidence ratio (SIR) 0.95, 95% CI 0.81–1.82), cancer of the salivary gland (SIR 0.72, 95% CI 0.29–1.49) or leukaemia (SIR 0.97, 95% CI 0.78–1.21). Nor did the risk of these cancers vary by duration of cellular phone use, time since first subscription, or type of phone (analogue or digital).
- 128** The new epidemiological information that has become available since the IEGMP Report, like that available to IEGMP, does not support the existence of a hazard of cancer from RF radiation in general, or specifically from the use of mobile phones. Thus, overall, the current results from epidemiological studies give no cause for concern in relation to TETRA. However, there are limits to the reassurance that they provide. In particular, they do not exclude the possibility that RF radiation from cellular phones might carry a risk of cancer that becomes manifest many years after first exposure or that relates to intense exposure over many years. Nor do they rule out a hazard from RF radiation modulated specifically at around 16 Hz.

Conclusions on biological effects

- 129** The possibility that exposure to low level RF fields amplitude modulated or pulsed at about 16 Hz results in changes in calcium ion movements in living tissues is much disputed. Generally, the design and interpretation of the studies that claimed to have demonstrated such effects were not ideal, and they were predominantly carried out using non-living tissue. A number of studies, generally better designed, have failed to detect an increase of calcium efflux from tissues as a result of RF exposure under a variety of conditions and modulations. Nonetheless, the sheer number of publications attesting to the phenomenon of calcium efflux cannot simply be ignored. Further research is needed, using modern molecular and cellular biology techniques, to assess the reliability of the positive findings and to determine the extent and significance of any effects that do occur.
- 130** The published literature does not necessarily represent the full range of experiments that have been performed in this field. There might have been other attempts to confirm the original observations on calcium efflux, which have not been published. In general, it is difficult to publish negative results, unless they definitively settle an important controversy. In this area of research there has already been a large number of publications, the early ones being mainly positive, the more recent ones largely negative. One more failure to replicate is unlikely to be of interest to scientific journals, even though it could be of crucial importance in helping to reassure users of the safety of amplitude-modulated and pulse-modulated communication systems.
- 131** Calcium plays an important role in many biological processes, especially in nerve cells. Substantial, maintained changes in calcium levels in the brain and cerebrospinal fluid of animals result in changes in the state of arousal, in feeding behaviour and in temperature regulation (Myers and Ross, 1981). Increase or decrease in calcium levels in the blood has pathological effects on heart and muscle. However, there is currently no evidence that exposure to modulated RF fields has such consequences.
- 132** If the phenomenon of calcium efflux is biologically significant, concomitant changes would be expected in the functions of nervous tissues that depend on the movement of calcium ions, but none has been unambiguously shown to occur. For example, changes in neuronal excitability have been reported, but mostly under conditions of exposure to RF fields that were likely to have caused biologically significant heating. Similarly, the changes in brain wave activity in animals that have been described occur with continuous-wave radiation, and may largely be attributable to heating. Suggestions that pulsed RF fields could trigger epileptic fits or otherwise affect epilepsy sufferers appear to be unjustified. Nevertheless, further studies could be undertaken exploring the effects of amplitude modulation on neuronal activity using *in vitro* models and strains of animals that are especially prone to epilepsy, while human volunteers studies could investigate whether exposure to the signals from TETRA hand portables induces any change in cognitive performance.
- 133** Although there is no epidemiological evidence specifically concerned with exposure to TETRA signals, or to RF radiation modulated at around 16 Hz, published epidemiological studies of RF exposure, including radiation modulated at other frequencies, give no cause for concern. However, they do not exclude the possibility of

a risk of cancer that appears only after many years of exposure, nor of a hazard from RF radiation modulated specifically at around 16 Hz.

- 134** A number of recent reviews have concluded that there are no established health risks associated with low level exposure to RF radiation, including modulated fields (Royal Society of Canada, 1999; IEGMP, 2000; Krewski *et al.* 2001; Zmirou, 2001). Although areas of uncertainty remain about the biological effects of low level RF radiation in general, including modulated signals, current evidence suggests that it is unlikely that the special features of the signals from TETRA mobile terminals and repeaters pose a hazard to health.
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RECOMMENDATIONS FOR FURTHER WORK

- 135** The Advisory Group has concluded that although areas of uncertainty remain about the biological effects of low level RF radiation, particularly about modulated signals, current evidence suggests that it is unlikely that the special features of TETRA systems pose a hazard to health. Nonetheless, a number of recommendations for further research are suggested by the Advisory Group following this review of the TETRA systems and the relevant experimental biology and epidemiology. These include proposals for experimental investigations of the possible biological effects of specific TETRA signals or RF radiation amplitude modulated at about 16 Hz as well as other frequencies using human volunteers, animals and cellular systems. Also recommended are physical and theoretical dosimetry studies to improve the assessment of the amount and pattern of absorbed energy from the use of hand portables or any other transmitting equipment deployed for use.

1 The existence of RF-induced changes in calcium efflux and its significance if it occurs in living tissue are much disputed. Further studies on the behaviour of calcium in tissues using modern molecular and cellular biology techniques should be used to determine the extent and significance of any effects that occur. In order to contribute to this field, any new study would have to be well designed, performed 'blind' as to the exact stimulus conditions in each trial, and preferably conducted with identical protocols in more than one well-respected laboratory.

2 If there are genuine changes in calcium efflux as a consequence of exposure to signals from TETRA, then the most likely effect would be on the functions of nervous tissue. Further studies need to be carried out on effects of amplitude modulation or pulsing on neuronal activity and on signalling within and between nerve cells.

3 The possibility that modulated RF fields might somehow synchronise the activity of groups of coupled neurons, and hence increase the likelihood of epileptic seizures could be investigated in isolated slices of rodent hippocampus, and also in strains of animals that are especially prone to epilepsy.

4 Possible mechanisms by which living cells might 'demodulate' amplitude-modulated RF fields should be investigated, using modern patch-clamp techniques. Particular attention should be paid to the identity of any non-linear element in cells that is capable of detecting the carrier frequency and therefore generating a current at the modulating frequency. Other possible mechanisms that have been suggested, including

direct influences on membrane proteins, should also be investigated both experimentally and theoretically.

5 Human volunteer studies should be carried out to measure changes in cognitive performance arising from exposure to TETRA handsets. They should include examination of the effect of varying parameters such as the duration of calls and extent of exposure, as well as signal characteristics.

6 The TETRA system is expected to be deployed widely for use by staff in emergency services. This is a relatively stable workforce with defined patterns of work. It would be worth carrying out studies to examine working practices and conditions of exposure to RF radiation from TETRA systems. Records of use should be kept, which could be of value in any future epidemiological studies.

7 The Independent Expert Group on Mobile Phones (IEGMP) recommended an audit of mobile phone base stations. This is now being carried out by the Radiocommunications Agency. TETRA base stations should be included in this audit. They should also be included in the database of base stations being developed by Government.

8 Only limited information is presently available on exposures from TETRA hand portables. Further work is needed to provide more information on exposures from hand portables and from any other transmitting equipment deployed for use. Exposures should comply with existing guidelines. Assessments of SAR for hand portables should be carried out using both experimental techniques and computational dosimetry.

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TETRA on the Internet

A list of websites is given in: TETRA Memorandum of Understanding Association (www.tetramou.com).

Appendix

GUIDELINES FOR PROTECTION

The exposures that people receive from TETRA equipment are discussed in the main report (paragraphs 57–77). The exposures are placed into context through comparison with the nationally and internationally advised restrictions on exposure that are summarised in this appendix.

This appendix is intended to give the minimum information that is necessary to support the main report and it is not intended to be a comprehensive review of the guidelines. The original documents should be consulted where clarification or further information is required.

Published guidelines relevant to the UK

National guidelines

The National Radiological Protection Board is an independent scientific organisation set up by the Radiological Protection Act (1970, as extended in 1974) with the responsibility to provide advice on the protection of people from radiation hazards. It also carries out research to underpin its advice and provides technical services. Following from this remit, NRPB has published guidelines on restrictions on human exposure to static and time-varying electromagnetic fields and radiation (NRPB, 1993). Recommendations in the document are derived from comprehensive reviews of relevant biological and human health studies carried out by NRPB staff and from advice by the Board's Advisory Group on Non-ionising Radiation. The NRPB guidelines specify the same basic restrictions for all people in all circumstances (ie both people who are occupationally exposed and members of the public).

There is no specific UK legislation requiring compliance with the NRPB guidelines, but the guidelines are widely used by Government departments and agencies. The Health and Safety Executive expects employers to follow NRPB advice as evidence that they have carried out their duties under the Health and Safety at Work etc Act 1974 and the Management of Health and Safety at Work Regulations 1999. Regulation 3 of the MHSW Regulations requires employers to make a suitable and sufficient assessment of risks to health and safety. The purpose of the assessment is to enable the employer to determine what measures should be taken to adequately control the risks arising out of the work activity. Consequently, the NRPB guidelines have been widely adopted in the UK.

International guidelines

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is an independent scientific organisation responsible for providing guidance and advice on the health hazards of exposure to non-ionising radiation. ICNIRP has also published guidelines for limiting human exposure to electromagnetic fields and radiation (ICNIRP, 1998a,b).

The ICNIRP guidelines differ from those published by NRPB in that they feature a two-tier basis that discriminates between public and occupational exposure. While the ICNIRP basic restrictions for occupational exposure are broadly in line with those

advised by NRPB for all people, ICNIRP has generally included reduction factors of up to five in setting its basic restrictions for the public. ICNIRP applies these reduction factors because the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals.

The profile of the ICNIRP guidelines has been raised recently within Europe because the European Council published a recommendation on limiting exposure of the general public to electromagnetic fields on 12 July 1999 (EC, 1999) and this document incorporates the ICNIRP public basic restrictions and reference levels. Several UK-based expert committees, including the Independent Expert Group on Mobile Phones (IEGMP, 2000), have all made recommendations involving the adoption of the ICNIRP guidelines in whole or part (Select Committee on Science and Technology, 1999; IEGMP, 2000).

The Government indicated in its response to the IEGMP report that the emissions from mobile phones and base stations should meet the ICNIRP guidelines for public exposure as expressed in the EC recommendation (DH, 2000). The Board of NRPB has accepted that the ICNIRP guideline for restricting exposure of the public should be adopted for mobile phone frequencies. The Government further agreed with the IEGMP recommendation that the guidelines do not need to be incorporated into statute.

Basic restrictions on exposure

The guidelines advise basic restrictions on exposure that are designed to ensure the avoidance of the established adverse health effects of exposure to radio waves. At radiofrequencies (RF) (above 10 MHz), these established adverse effects arise at levels of exposure where appreciable heating of the body tissues is able to occur due to the absorption of the energy carried by radio waves. Heating can occur, either in parts of the body due to localised absorption of RF, or more generally throughout the body. Consequently, basic restrictions are specified to cover both situations and they must all be complied with to ensure compliance with a given set of guidelines. The basic restrictions advised by NRPB and ICNIRP are expressed in terms of the specific absorption rate (SAR) of energy and they are shown in Table A1.

Exposure may be averaged over periods of several minutes for comparison with the basic restrictions. It is therefore possible to be exposed to SARs above the basic restrictions for periods less than the averaging time, without any hazard being posed. Rates of energy absorption below the basic restriction can be accommodated by the body's thermoregulatory system and so they would not be expected to produce harmful temperature rises, even with continuous exposure.

The averaging masses given in the basic restrictions are not specified over tissue regions of any particular geometrical shape, eg a cube. They are specified to be over contiguous regions of tissue, ie arbitrarily shaped regions within the same tissue type, or organ.

When a mobile radio handset is held close to a user's head, a proportion of the radiated power is absorbed in the tissues of the head. The amount of power absorbed and the spatial distribution of the absorption in the head tissues depends on factors such as the design of the handset, how it is held in relation to the head and the operating frequency. Under these exposure conditions, it is the basic restriction on localised exposure in the head that will be most restrictive.

Basic restriction	SAR in $W\ kg^{-1}$ [averaging mass in grams] (averaging time in minutes)					
	ICNIRP general public		ICNIRP occupational		NRPB (all people)	
SAR averaged over the entire body mass	0.08	(6)	0.4	(6)	0.4	(15)
Localised SAR in the head*	2	[10] (6)	10	[10] (6)	10	[10] (6)
Localised SAR in the neck and trunk	2	[10] (6)	10	[10] (6)	10	[100] (6)
Localised SAR in the limbs	4	[10] (6)	20	[10] (6)	20	[100] (6)

TABLE A1 Basic restrictions advised by NRPB and ICNIRP over the frequency range 10 MHz to 10 GHz

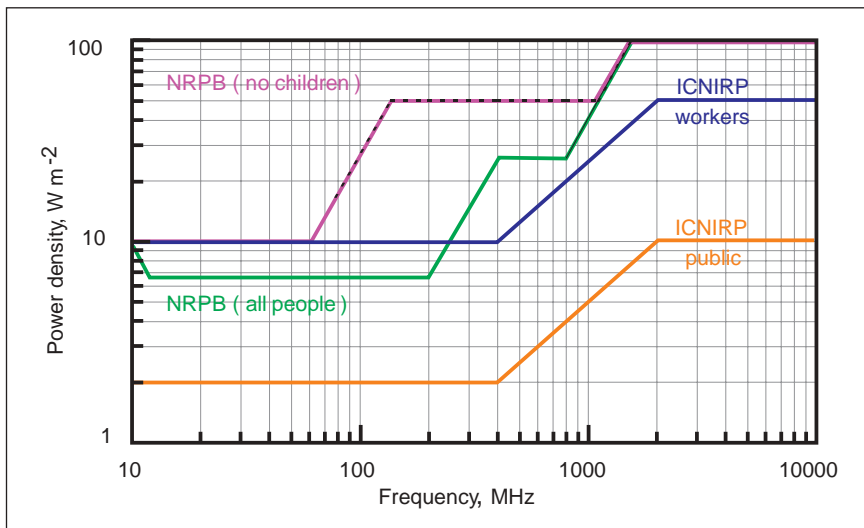
*Also applies to fetus in case of NRPB.

Investigation/reference levels

Since SARs cannot be measured in living people, the NRPB guidelines specify investigation levels in terms of field strengths and power densities. These are derived so that the basic restrictions cannot be exceeded under certain conditions. If an investigation level is exceeded, more detailed investigation of the resultant SAR is indicated. The conditions chosen for setting investigation levels involve exposure of the whole body to a plane electromagnetic wave over the 10 MHz to 10 GHz frequency range and should prove conservative over other exposure conditions where the coupling of the field to the body would not be expected to be so strong.

At frequencies between 10 MHz and 1.55 GHz, energy absorption can be strongly dependent on the size of the human body, and the whole-body SAR in small children may be higher than in adults exposed at the same power density. Consequently, the NRPB guidelines also contain a second higher set of investigation levels that may be used over this frequency range if there is no possibility of small children being exposed.

The ICNIRP guidelines specify quantities similar to the NRPB investigation levels and term them reference levels. ICNIRP also uses different dosimetric models to NRPB



Variation of the ICNIRP reference levels and the NRPB investigation levels as a function of frequency

TABLE A2
Investigation/
reference levels
taken from the
NRPB and ICNIRP
guidelines

Guidelines	Investigation/reference level in terms of power density ($W m^{-2}$)			
	Airwave mobile 380–393 MHz	Airwave base 390–393 MHz	Dolphin mobile 410–415 MHz	Dolphin base 420–425 MHz
NRPB (all people)	23.8	25.1	26.0	26.0
ICNIRP occupational	10.0	10.0	10.2	10.5
ICNIRP general public	2.0	2.0	2.0	2.1

in order to analyse the physical interaction of electromagnetic fields with the body. For this reason, the ICNIRP reference level for workers is noticeably different to the NRPB investigation level for populations excluding children, even though the underlying basic restrictions are broadly the same.

Coupling of the body to an electromagnetic field varies with frequency and it is strongest at frequencies around 40–80 MHz. In this frequency range, the wavelength of the electromagnetic field is comparable in size to that of the body dimensions so that resonance occurs, as with an antenna. The investigation/reference levels are therefore most restrictive in this part of the spectrum in order to remain conservative over the basic restrictions. A graph showing the variation of the levels with frequency is shown in the figure.

When considering people's exposure to TETRA base station signals, where the whole body is likely to be exposed, it is easier to compare the measured power density with the reference/investigation levels. Their values at the frequencies used for TETRA in the UK are shown in Table A2.

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Glossary

TERMINOLOGY ASSOCIATED WITH TETRA

Base station fixed equipment used for relaying communications between mobile terminals. Each base station serves a geographical area, known as a cell, and the combination of all the cells in a network defines the area covered by that network.

Direct Mode Operation (DMO) mode of operation by which mobile terminals communicate with each other directly without the radio signals being relayed by a base station.

Fixed mobile a vehicle-mounted terminal used temporarily at a fixed location.

Hand portable a portable mobile terminal, normally held close to the head or waist of the user. Hand portables are similar in appearance to mobile phones.

Mobile terminal mobile equipment that is used to obtain TETRA services. Mobile terminals include vehicle-mounted terminals and hand portables.

Repeater a mobile transceiver used for providing a radio link between base stations and mobile terminals in order to give additional coverage in a particular area.

TETRA TERrestrial TRunked RAdio is the modern digital Private Mobile Radio (PMR) and Public Access Mobile Radio (PAMR) technology.

Trunked Mode Operation (TMO) mode of operation by which communications between mobile terminals are routed via base stations.

Vehicle-mounted terminal a mobile terminal built into a vehicle and connected to an antenna mounted on the outside of the vehicle.

POWER MODULATION SPECTRA OF SIGNALS USED IN TETRA

Technical Note

PREPARED BY S M MANN AND L J CHALLIS FOR THE
ADVISORY GROUP ON NON-IONISING RADIATION

This Technical Note reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

Executive Summary

- 1** This Technical Note gives information on the characteristics of radio signals from base stations and mobile terminals using Terrestrial Trunked Radio (TETRA) at frequencies around 400 MHz. The data are drawn from measurements carried out by NRPB, published technical standards for the design and operation of the TETRA system, and from detailed technical discussions with manufacturers and operators. The Technical Note provides information supplementary to that given in the main report.
 - 2** Waveform measurements of base station emissions were made at operational radio sites in the BT Airwave network intended for the emergency services and in the commercial network operated by Dolphin Telecom. Measurements were also made of base station emissions under laboratory conditions at Simoco Digital Systems in Cambridge. Further measurements were made of the emissions from TETRA hand portable terminals transmitting in Trunked Mode Operation (TMO: terminals communicating through the base station network) and Direct Mode Operation (DMO: terminals communicating directly between each other).
 - 3** The measurements confirm that, to within the limits of the precision of the measurement technique (less than 1%), TETRA base station signals are continuous and not pulsed over time intervals that could cause amplitude and therefore power modulation at frequencies between 1 and 200 Hz. This conclusion is consistent with the TETRA technical standard and with information obtained in the course of technical discussions with network operators and system manufacturers.
 - 4** TETRA uses phase modulation rather than amplitude modulation to encode data on to its radio signals. However, the transmitted signals normally exhibit significant amplitude variations, because of the filtering that is applied after modulation. These variations are effectively random over time and the average power emitted is constant over time intervals comparable to or larger than the timeslots in which the transmission occurs.
 - 5** Under certain conditions, for example when there is little call traffic, the amplitude variations in base station signals can cease for periods of 1.78 ms in some or all of the 14.17 ms timeslots. However, the TETRA system is designed to ensure that the power emitted during these constant amplitude periods is the same as the average power at other times.
 - 6** Power modulation does occur in the transmissions from Dolphin and Simoco base stations at a very low frequency of 0.245 Hz. This arises from 6 ms breaks in the transmission at 4.08 s intervals when the base stations make corrections to their power amplifiers. Breaks in transmission do not occur with BT Airwave base stations while these corrections are carried out and so no power modulation is introduced.
 - 7** In contrast to those from base stations, the waveforms from TETRA mobile terminals are not continuous but are pulsed. The transmission includes bursts in which the power is ramped up at the beginning and then down at the end of each timeslot used. This leads to pulsing at 17.64 Hz and its harmonics. The relative strengths of the harmonics depend on whether the mobile terminal is being used for DMO or TMO, but should not depend significantly on the make or model.
-

INTRODUCTION

- 1 This Technical Note gives additional information on the characteristics of radio signals emitted from base stations and mobile terminals using Terrestrial Trunked Radio (TETRA) at around 400 MHz. The measurements have been made by NRPB and provide supplementary technical information to that given in the main report.
 - 2 During the present work, waveform measurements were made at operational radio sites in the BT Airwave and Dolphin Telecom networks, as well as under laboratory conditions at Simoco Digital Systems in Cambridge. While at Simoco, the opportunity was also taken to make measurements of the waveforms from TETRA hand portable terminals transmitting in Direct Mode Operation (DMO) and Trunked Mode Operation (TMO). These data are contrasted with the results for base stations.
 - 3 The Technical Note begins with two sections that describe the background theory and contain information that is essential to the interpretation of any measurements of TETRA signals made using a spectrum analyser. The digital modulation system that TETRA uses to encode a stream of binary data on to a radio carrier is first described. The next section describes the structural aspects of TETRA signals and their bursts that affect the power spectra of its radiated signals.
 - 4 Subsequent sections describe the measurements that were made and how they were analysed to determine the degree of modulation at various frequencies. First there is a consideration of base stations made by Nokia (used by Dolphin), Motorola (used by BT Airwave) and Simoco. A Simoco SRP1000 hand portable was used to produce examples of mobile terminal waveforms and the results are presented for Trunked Mode Operation (TMO) and then Direct Mode Operation (DMO).
 - 5 This Technical Note draws on the TETRA technical standard (ETSI, 1998, 2000) and reference is made to relevant sections of this standard, where appropriate. Background information on digital modulation schemes and their associated terminology is given in Appendix A. Those not familiar with TETRA and signal modulation may find it helpful to read Appendix A first.
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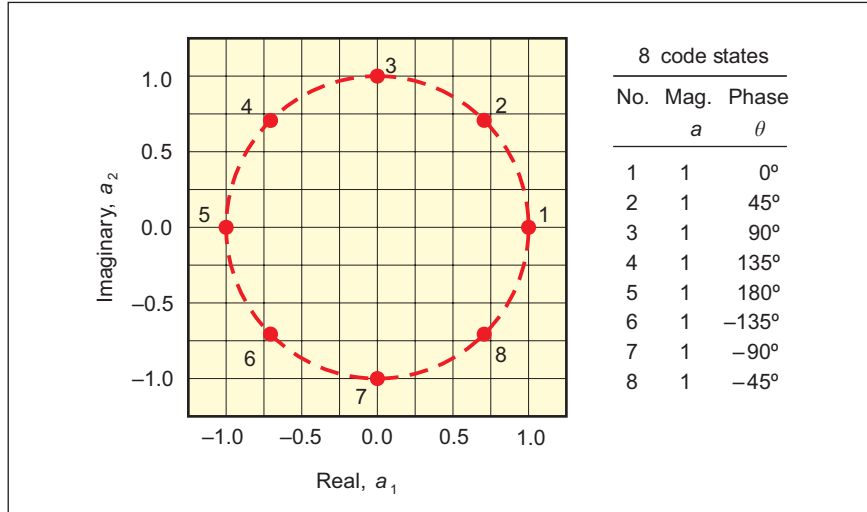
DQPSK MODULATION IN TETRA

- 6 The modulation scheme used by TETRA is known as Differential Quaternary Phase Shift Keying (DQPSK). It is a digital modulation scheme that is used to encode a stream of binary data at a given bit rate on to a radiofrequency carrier signal. General information about digital modulation schemes and their terminology is given in Appendix A and further details about DQPSK in TETRA are given in the technical standard (ETSI, 2000: Section 5).

DQPSK constellation chart

- 7 The DQPSK system is described as *quaternary* because it uses the four phase changes: -135° , -45° , $+45^\circ$ and $+135^\circ$ to move between the eight code states shown in the constellation chart (Figure 1). The axes of the constellation chart are the real and imaginary components of the complex number $a \exp(j\theta)$, where a is the signal magnitude and θ is its phase.

FIGURE 1 Signal constellation chart for DQPSK



8 The system is described as *differential* because it is the changes in phase over set time intervals that carry the signal information, rather than the absolute phase at regular points in time. The four possible phase changes are known as *symbols*.

Symbol mapping scheme

9 Each of the four symbols used in DQPSK can be used to represent two bits of binary data and the symbol-mapping scheme used by TETRA is shown in Table 1.

TABLE 1 Binary mapping scheme used with DQPSK in TETRA

First bit	Second bit	Symbol (phase change)
1	1	-135°
1	0	-45°
0	0	+45°
0	1	+135°

Data and symbol rates

10 TETRA uses the DQPSK scheme to encode a datastream at a rate of 36 k bit s⁻¹ so that one bit of data is encoded around every 28 μs. Since two bits of data are modulated on to every symbol, the symbol rate is half the data rate and one symbol is transmitted every 56 μs. This 56 μs period will be referred to as the *modulation interval*.

11 If the transmission is at the carrier frequency, f_c , the number of waveform cycles during a modulation interval, N_c , is $f_c \times 56 \times 10^{-6}$. Therefore $N_c = 22\,400$ cycles for a TETRA signal at 400 MHz. In order to achieve phase changes of $\pm 45^\circ$ and $\pm 135^\circ$ over the modulation interval, N_c has to change by $\pm (1/8)$ and $\pm (3/8)$ of a cycle, respectively. These correspond to changes in the average frequency over the modulation interval of $\pm (1/8) \times (1/56 \times 10^{-6})$ and $\pm (3/8) \times (1/56 \times 10^{-6})$, ie ± 2.25 or ± 6.75 kHz, respectively.

Signal trajectory

12 The modulation can be plotted on a constellation chart in the form of a trajectory moving over time between the various code states. Initially, ie before the signal has

been filtered, all of the phase changes lie on the dashed circle shown in Figure 1, so that the amplitude of the signal, which is its distance from the centre of the circle, is constant. However, the discontinuous changes in direction that occur during the trajectory lead to a broad frequency spectrum and, to reduce this, the signal is passed through a *root raised cosine filter* (ESTI, 2000: Section 5.5). This constrains the spectrum to within a bandwidth of 25 kHz but also has the effect of causing the amplitude and hence the power of the signal to vary with time.

- 13** The effect of the filter can be seen in Figure 2 which is a plot of the first 14 ms of a datafile provided by Simoco Digital Systems. The file contained around 200 ms of modulated and filtered TETRA signal captured from a base station transmitter and samples were taken every 13.9 μs (a total of 14 627 real and imaginary pairs). The data in the figure were normalised to the root mean square (RMS) power of the signal.
- 14** It can be seen that after filtering, the signal trajectory no longer changes sharply in direction as it moves about the constellation chart from one symbol to the next and the changes in direction are now accomplished smoothly. It is also clear that large changes in amplitude, S_m , occur during the trajectory resulting in the very significant variations in power that are displayed and analysed statistically below.

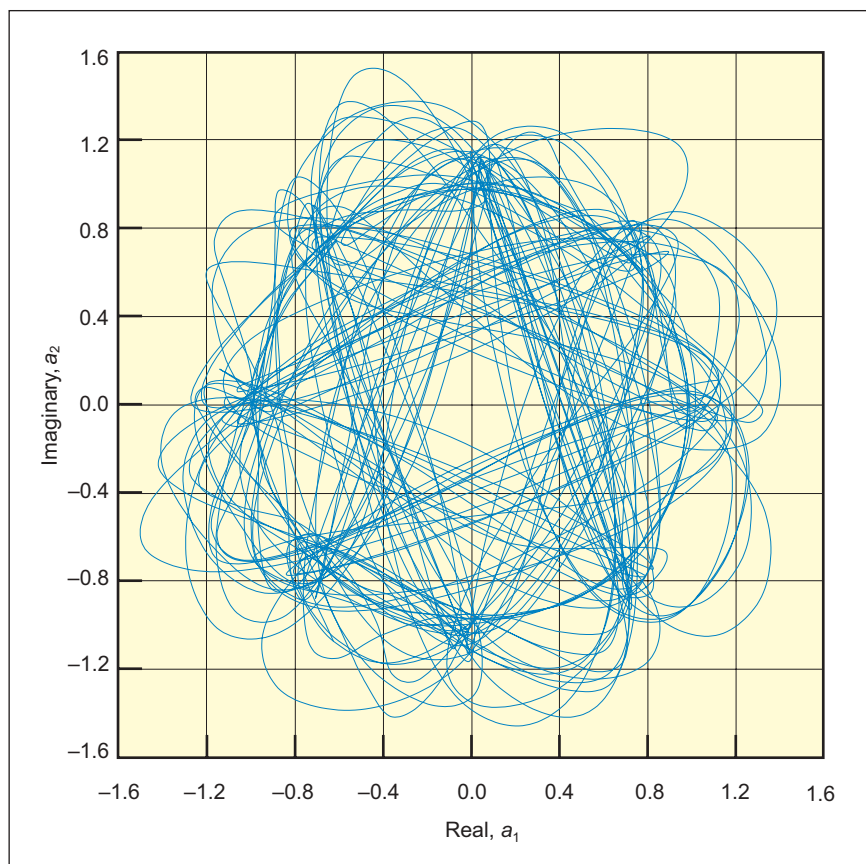
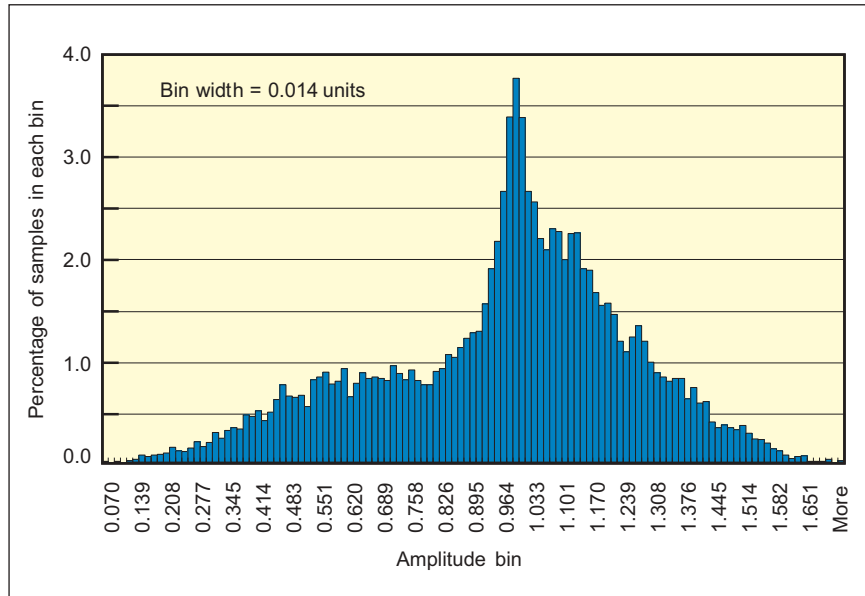


FIGURE 2
Amplitude and
phase evolution of a
TETRA signal over a
period of 14 ms

FIGURE 3
Histogram showing the variation of the amplitude of a modulated TETRA signal



Power statistics

- 15 The variations in the normalised signal amplitude, S_m , of the TETRA signal are displayed as a histogram in Figure 3. The amplitude samples ranged from 0.07 to 1.72 of the normalised RMS signal amplitude. Since the signal power is proportional to the square of its amplitude, the histogram of the power variations would have a qualitatively similar form, although the variations from the average power would be even greater.

TETRA SIGNAL STRUCTURES

- 16 The structure of the TETRA signal includes the various types of burst used to monitor and control the signal levels, frequencies etc of the mobile terminals and control access to the base stations. These features will not be discussed in detail here but a description of some of them is required to explain the results presented later in this document. Section 9 of the technical standard (ETSI, 2000) provides further details.

Frame structures and hierarchy

- 17 The shortest time interval that has any significance in terms of the radio aspects of TETRA is the $56 \mu\text{s}$ length of the modulation symbol, which encodes 2 bits of information. Groups of 510 bits (255 symbols) are assembled into bursts that occupy timeslots each lasting for 14.17 ms.
- 18 There are four timeslots in each 56.67 ms frame and 18 frames then fill each 1.02 s multiframe. It should be noted that every 18th frame is designated a control frame. Finally, 60 multiframe fill one 61.2 s hyperframe (ETSI, 2000: Section 9.3.1). This overall structure is shown in Figure 4.

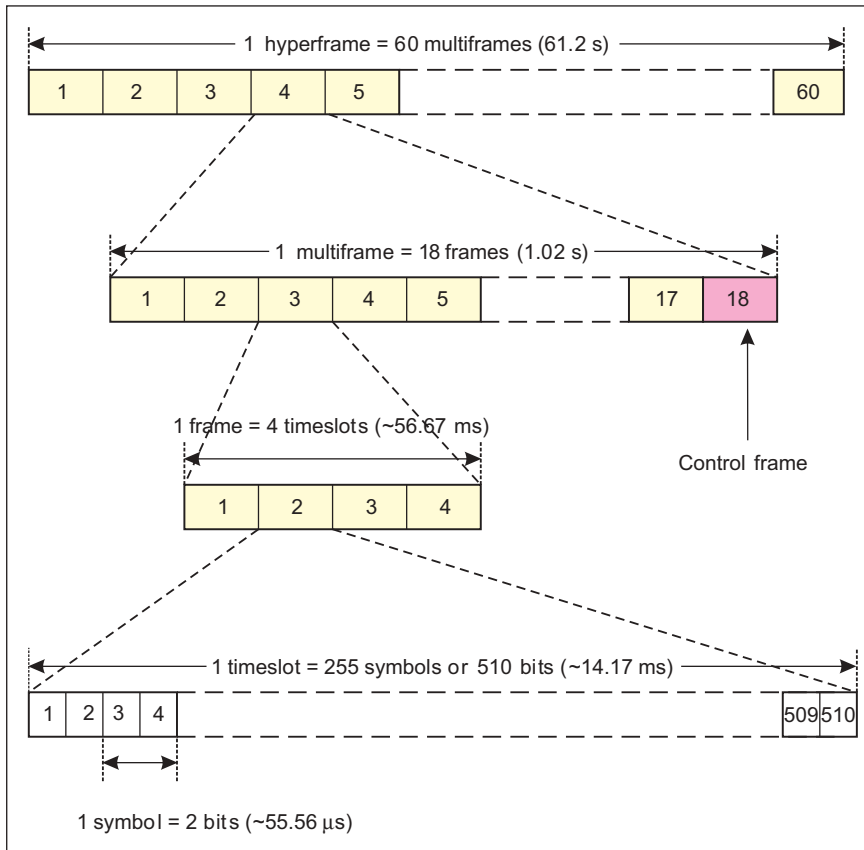


FIGURE 4
Hierarchy of the
frame and timeslot
structures used
with TETRA

Continuous and discontinuous modes

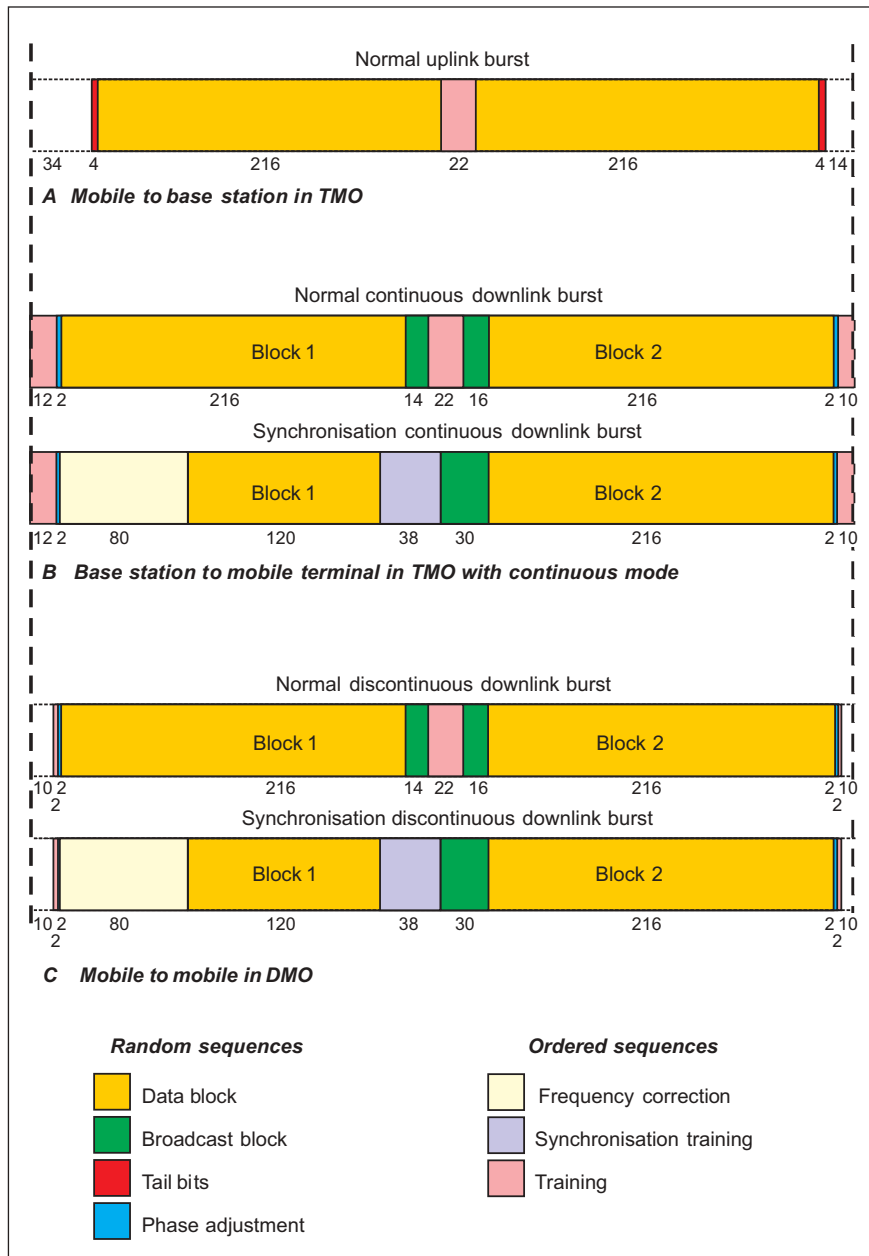
- 19 The TETRA technical standard permits base stations to use either continuous or time-sharing (discontinuous) modes for transmission (ETSI, 2000: Section 9.4.5). In discontinuous mode, the power is ramped up over a short period of time at the beginning of each burst and then back down again at the end of the burst (ETSI, 2000: Section 6.4.5). This mode allows up to four base stations to share the same frequency channel by transmitting in turn; however, it is not used by Dolphin or BT Airwave.
- 20 Base stations used in the UK only operate in continuous mode, where they transmit through all four timeslots in each frame (except when the BLCH is active, see paragraphs 30–32) and their output power remains constant across timeslot boundaries.
- 21 TETRA mobile terminals use discontinuous mode when they are only using one timeslot in each frame for transmission. If the mobile terminals use more than one timeslot in each frame, the technical standard allows the transmitted power to remain continuous across boundaries.

Burst types and structure

- 22 The purpose of the 510 bits (255 symbols) that can be transmitted in each timeslot depends on the type of burst that occupies the timeslot. Many different types of burst can be used in TETRA (ETSI, 2000: Section 9.4) and some of these are illustrated in Figure 5.

23 It is not necessary to describe the detailed structure of all of the different types of bursts used in TETRA for the purpose of this document, but it is important to highlight certain features in order to explain the measurement results presented later in this document.

FIGURE 5 Some of the different types of burst that can be used in each timeslot by TETRA transmitters



- 24** Some portions of the various bursts always consist of the same sequence of ones and zeros whenever they are used. These have been termed *ordered sequences* in Figure 5 (ETSI, 2000: Section 9.4.4.3). The other parts of the bursts consist of essentially random sequences of binary data that differ from one burst to the next.

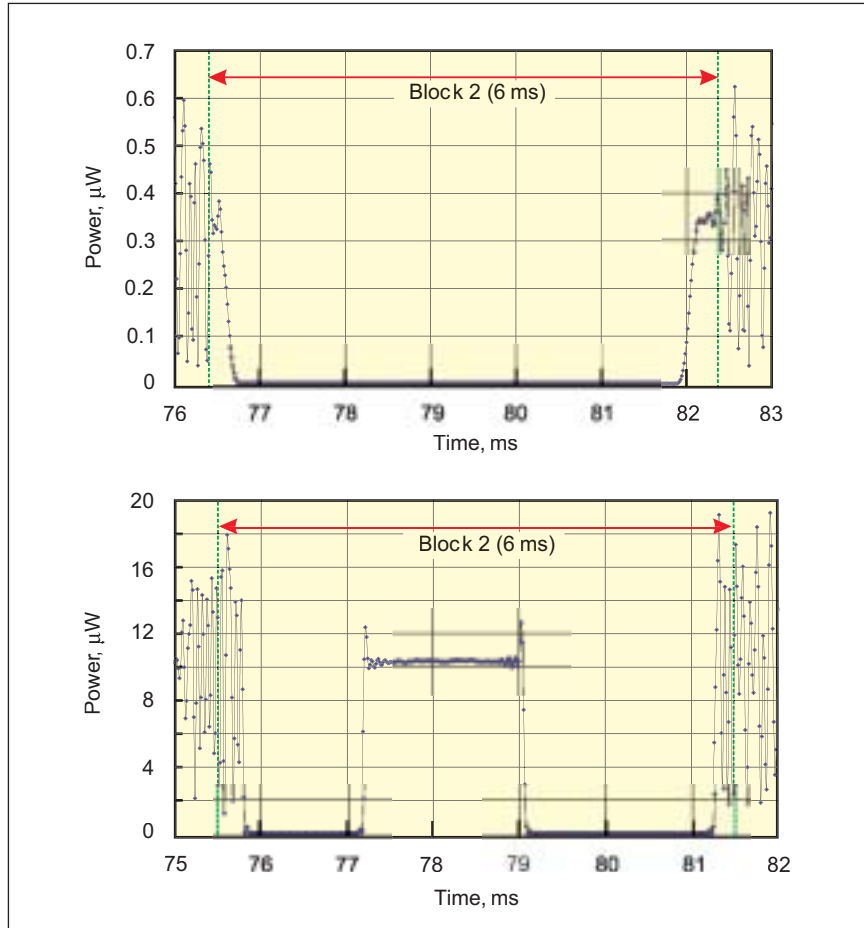
Synchronisation continuous downlink burst

- 25** TETRA base stations operating in continuous mode can transmit either normal continuous downlink bursts (NCDBs) or synchronisation continuous downlink bursts (SCDBs) in the four timeslots of every frame. SCDBs contain a period during which the frequency correction channel (FCCH) is active and this period always contains the same ordered sequence of modulated bits.
- 26** The FCCH is active during bits 15–94 in the SCDB. Bits 15–22 and 87–94 are continuous ones, and bits 23–86 are continuous zeros (ETSI, 2000: Section 9.4.4.3.1). Table 1 shows that the continuous-ones portion of the burst will result in a succession of -135° phase changes and consequent power variations as the trajectory moves across the constellation chart and away from the circular locus linking the code states. The 64 continuous zeros will lead to a succession of $+45^\circ$ phase changes (increase in frequency by 2.25 kHz), which will cause the signal to move around the constellation chart following a circular trajectory of constant power.
- 27** The duration of the period of constant power while the 32 consecutive $+45^\circ$ phase changes (64 data bits) in each SCDB are transmitted will be 1.78 ms. The base station signal is effectively a pure sinusoid of frequency 2.25 kHz greater than the nominal carrier frequency over this period. Hence, the signal bandwidth will become narrower during this period than at other times when frequency shifts of ± 6.75 kHz can occur. It is important therefore that the spectrum analyser used to measure the TETRA base station signal has a bandwidth that is sufficiently wide to avoid the introduction of spurious power variations at 17.64 Hz and its harmonics that are not actually present in the signal.
- 28** The measurements made during this work indicated that timeslot 1 of the main carrier from Dolphin and Simoco base stations always contains a NCDB, and timeslots 2, 3 and 4 contain SCDBs when no calls are being handled. NCDBs are substituted for the SCDBs in the appropriate timeslot when call traffic is present. All four timeslots in the carriers from a BT Airwave base station are able to contain either NCDBs or SCDBs.
- 29** It should be noted that it is not mandatory in the TETRA standard for base stations to transmit SCDBs in unused timeslots, but this technique is used by some base station manufacturers because it helps mobile terminals to retain synchronisation at all times. Once call traffic starts, the timeslots that are being used contain NCDBs, except for frame 18 of every multiframe where it is mandatory for SCDBs to be transmitted.

Base station linearisation channel

- 30** At regular intervals, no more frequent than once every 4.08 s (every four multi-frames), the Base Station Linearisation Channel (BLCH) can become active in one of the four timeslots of the control frame (timeslot 18 of the multiframe). Base stations use this period to linearise their power amplifiers and the behaviour of the transmitted waveform at this point and the precise timeslot used may differ from manufacturer to manufacturer. In all cases, the waveform behaviour is only affected during Block 2 (bits 283–498) of the burst, and hence for a period of 6 ms (ETSI, 2000: Section 9.5.2).

FIGURE 6
Waveform characteristics from Dolphin (top) and Simoco (bottom) base stations while the BLCH is active



31 The BLCH is active once every 4.08 s with Dolphin base stations and, while it is active, the output power is ramped down to zero for a period of around 5.5 ms. Simoco transmitters also activate the BLCH once every 4.08 s and their output power is ramped down and up twice, once at the beginning of the BLCH and once at the end. Measurements with BT Airwave base stations showed no changes in their transmitted power to indicate that the BLCH was active. Motorola (the manufacturer) subsequently indicated that the BLCH is active every 16 minutes and 19.2 s with BT Airwave base stations and it does not cause a break in transmission. Examples of waveform characteristics during the BLCH from Dolphin and Simoco base stations are shown in Figure 6.

32 For this work, it will be assumed that all base stations transmit zero power throughout the entire duration of Block 2, since this will give rise to the maximum amount of power modulation at 0.25 Hz. It will also be assumed that the BLCH is active in timeslot 1 of the control frame.

BASE STATION SIGNALS

- 33** There are (at least) three different manufacturers of TETRA base stations. The main suppliers to the two UK networks are Nokia, which supplies base stations to Dolphin Telecom, and Motorola, which supplies base stations to BT Airwave. Simoco Digital Systems manufacture base stations in the UK and Ireland and supply them to the Isle of Man Police, but not to Dolphin or BT Airwave.
- 34** For this work, measurements were made with a Simoco base station in a laboratory at the company's Cambridge premises, with a Dolphin base station installed at a site near the NRPB Chilton site and with a BT Airwave base station in Lancashire. The Dolphin and BT Airwave base stations were selected from a list of sites provided by each operator; however, the operator was not aware which site was chosen from the list nor when the measurements were made.
- 35** The data for the Simoco base station have been used for illustrative purposes in the graphs in this section because they were obtained under laboratory conditions. Where differences were observed with the base stations of the other manufacturers, as depicted in the BT Airwave and Dolphin networks, this is noted.

Measurement system

- 36** The base station signals were measured using a Hewlett Packard E4407B Spectrum Analyser, directly connected to the output from the Simoco base station through a cable and attenuators. Measurements with the Dolphin and BT Airwave base stations were made at operational radio sites and, for these, the spectrum analyser was connected to a log-periodic receiving antenna mounted on a tripod. The antenna was directed towards the radio masts, several hundred metres away.
- 37** The separation of the frequency channels in the TETRA bands is 25 kHz, consequently the spectrum of each signal would be expected to be somewhat narrower than this. Accordingly, the bandwidth of the spectrum analyser was set to 100 kHz to ensure that all of the signal power was captured. The video bandwidth was set equal to the resolution bandwidth and the detector of the spectrum analyser was set to sample mode in accordance with advice from the manufacturer (Street, 2001).
- 38** The centre frequency of the spectrum analyser was set equal to that of the displayed base station signal and then the frequency span was reduced to zero so the screen display became the power of the measured signal as a function of time. The number of data points (samples) across the screen was set to the maximum possible, ie 8192, and then the total time interval across the screen was set equal to that of two complete frames, ie 113.4 ms.
- 39** With these settings, the interval between samples is 13.8 μ s. This is slightly greater than the minimum sampling interval possible with the spectrum analyser of 10 μ s. However, since this permits 4.1 samples to be taken during each symbol, it should provide a good description of the signal modulation on the constellation chart. It is also of note that this method of using the analyser was that recommended by the manufacturer which also indicated (Street, 2001) that the sample values were effectively instantaneous values rather than values averaged over a period of time comparable to the sample interval.

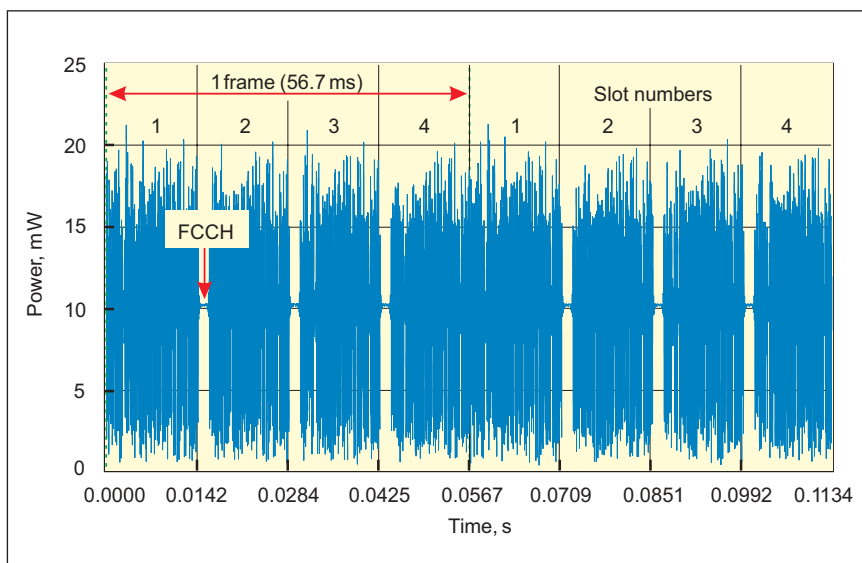
Time domain results

- 40** The spectrum analyser was used to capture the output power waveform from the Simoco base station over a period of 113.4 μ s, or two complete frames. The average

power of the measured waveform was 9.95 mW and it can be seen that timeslot 1 contains a normal continuous downlink burst (NCDB) and timeslots 2, 3 and 4 contain synchronisation continuous downlink bursts (SCDBs). The timeslot boundaries were therefore identified in the sampled data with reference to the 1.78 ms periods of constant power in the SCDBs when the frequency correction channel (FCCH) was active. The results are shown in Figure 7 and similar data were found with the Dolphin and BT Airwave base stations at operational radio sites.

- 41 The power variations in Figure 7 correspond to the amplitude variations in the distance of the signal from the centre of the constellation chart over time. The statistics of the power variations would therefore match the histogram shown in Figure 5 if it were re-plotted in terms of the amplitude squared, which is proportional to the power.
- 42 The 1.78 ms periods of constant output power in the SCDBs were seen to disappear from time to time with the operational base stations. This was assumed to be because NCDBs were being substituted in timeslots 2, 3 and 4 when calls were taking place. The BT Airwave base station also showed periods where all four of its timeslots contained SCDBs.
- 43 The next step was to Fourier analyse the signals and transform to the frequency domain in order to search for systematic power modulation at low frequencies.

FIGURE 7 Power variations in the modulated signal from a TETRA base station over two complete TDMA frames showing the timeslot boundaries



Frequency domain results

- 44 The data used to plot Figure 7 were first concatenated 36 times to produce a file containing four complete multiframe. Then, timeslot 1 of frame 18 in the 4th multiframe was modified to include a simulated base station linearisation channel (BLCH) with 6 ms at zero power, as described in paragraphs 30–32. This 4.08 ms of data was then taken to be a single period of base station output waveform, whose spectrum could be analysed through Fourier methods.

- 45** In order to produce more finely separated frequency bins in the output from a fast Fourier transform, the basic function generated above was concatenated a further six times in order to produce a total of 24 multiframe in which every 4th multiframe contained a simulated BLCH. This file contained a total of 1 769 472 samples that would have been difficult to transform directly and so cubic spline interpolation was used to resample the data to form an array containing 2 097 152 ($= 2^{21}$) equally spaced samples. The bin separation in the resulting Fourier transform was consequently 0.0408 Hz and the Nyquist frequency was 36 kHz. A Hann window was applied to the input data of the transform. This standard technique reduces distortions in the frequency spectrum that occur due to the truncations of the time domain dataset.
- 46** The bins in the Fourier transform were normalised to the burst-averaged power of the base station signal (see Appendix A) in order to obtain the spectrum of the power modulation function and the result is shown in Figure 8.

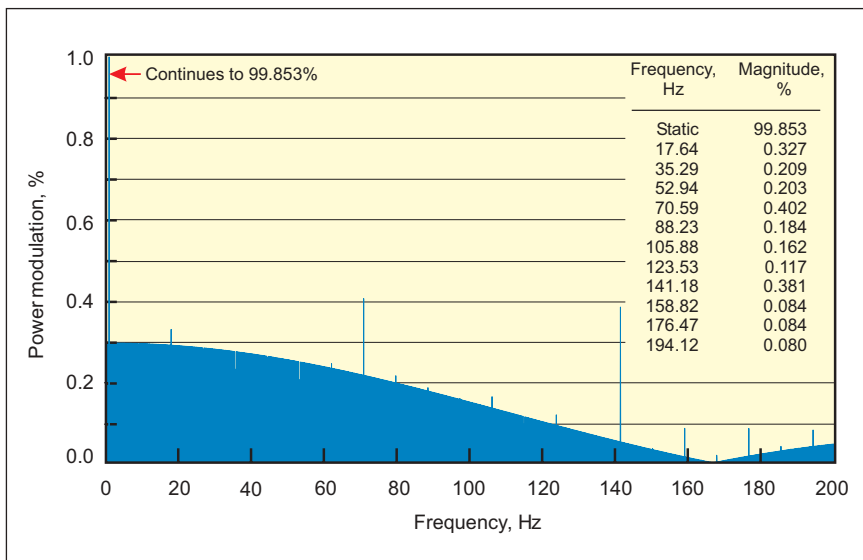


FIGURE 8 Power modulation spectrum for the output signal from a TETRA base station with a simulated BLCH inserted into every 4th multiframe

- 47** The transform shows several frequency components in the power modulation spectrum at multiples (harmonics) of the 17.6 Hz frame rate in the signal. There are also many finely spaced harmonics of the 0.25 Hz frequency associated with activity of the BLCH and some of these coincide with the 17.6 Hz harmonics. The amplitudes of the 0.25 Hz harmonics progressively reduce with increasing frequency until they become zero at a frequency of 167 Hz before beginning to rise again (167 Hz is the reciprocal of the 6 ms BLCH duration).
- 48** Since the 6 ms breaks in transmission that occur every 4.08 s when the BLCH is active occupy 0.15% of the total time, the static (average) power component is 99.85% of the peak power. All of the individual time-varying components in the power modulation spectrum have coefficients that are less than 0.5% of this static power.
- 49** The largest component of power modulation found in the base station signal is 0.40%, and this occurs at a frequency of 70.6 Hz, corresponding to the timeslot rate in

the signal. Power modulation at some of the 17.6 Hz harmonics was not visible because it was obscured by the 0.25 Hz harmonics and so two more figures were plotted. Figure 9 examines in finer detail the first 20 Hz of Figure 8 to show the 0.25 Hz harmonics and Figure 10 is based on a transform of the same input dataset as Figure 8 but with no BLCH inserted, so the 0.25 Hz harmonics are removed.

50 Figure 10 shows that the 70.6 Hz contribution is reduced to around half of that shown in Figure 8 by the removal of the 0.25 Hz harmonics and the contribution is now 0.34% at 141 Hz. This component is unlikely to arise purely because it is the second harmonic of the 70.6 Hz timeslot rate and so it must be due to a systematic power variation that has two cycles in every burst.

FIGURE 9 Power modulation spectrum for the output signal from a TETRA base station showing the 0.25 Hz components due to the BLCH

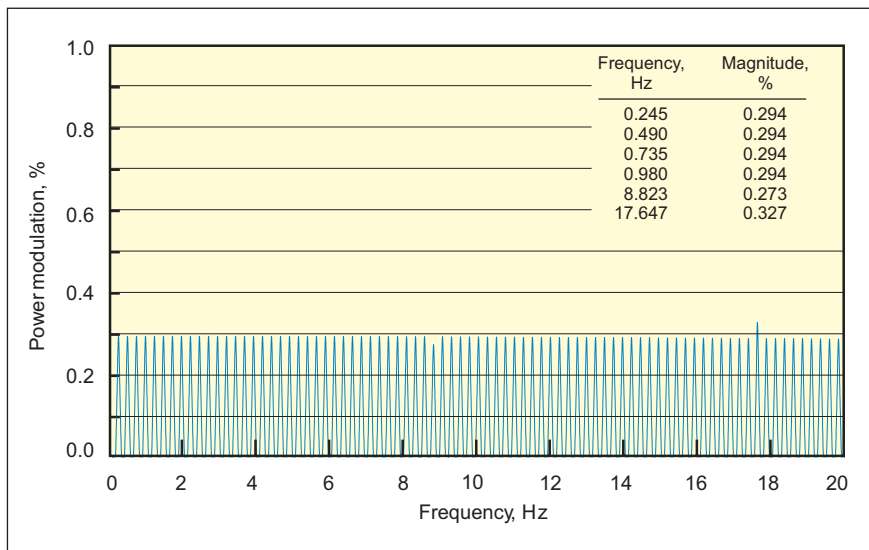
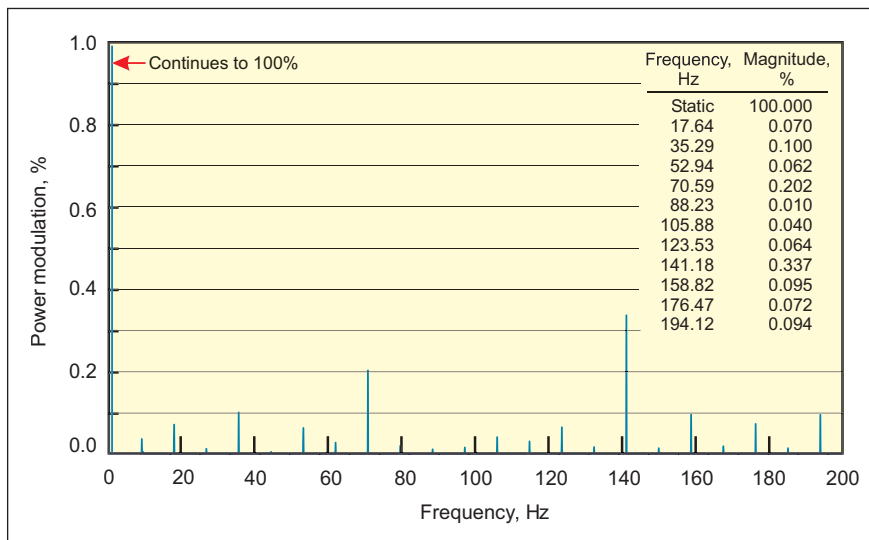


FIGURE 10 Power modulation spectrum for the output signal from a TETRA base station with no BLCH inserted



- 51 With such small amounts of power modulation present it is not possible to conclude that the power modulation observed is an inherent feature of the TETRA signal since coefficients of this size could be artefacts associated with the way the time domain data were acquired and processed. This is discussed further in Appendix B where it is shown that comparable coefficients would arise from statistical fluctuations.
- 52 It is also of note that the figures show harmonics of 8.8 Hz, which has no relation to any structure in the real signal and must result from the data processing. The first sampled frame has an average power of 9.948 mW, while the second sampled frame has an average power of 9.959 mW. Cascading these two frames thus artificially introduces a power variation at a frequency of 8.8 Hz into the input dataset of the Fourier transform.
- 53 The analysis in this section was repeated for waveforms sampled from Dolphin and BT Airwave base stations. The results were found to be generally consistent with those presented here and the harmonic coefficients are given in the summary and conclusions section (Table 2).
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MOBILE TERMINAL SIGNALS IN TRUNKED MODE OPERATION

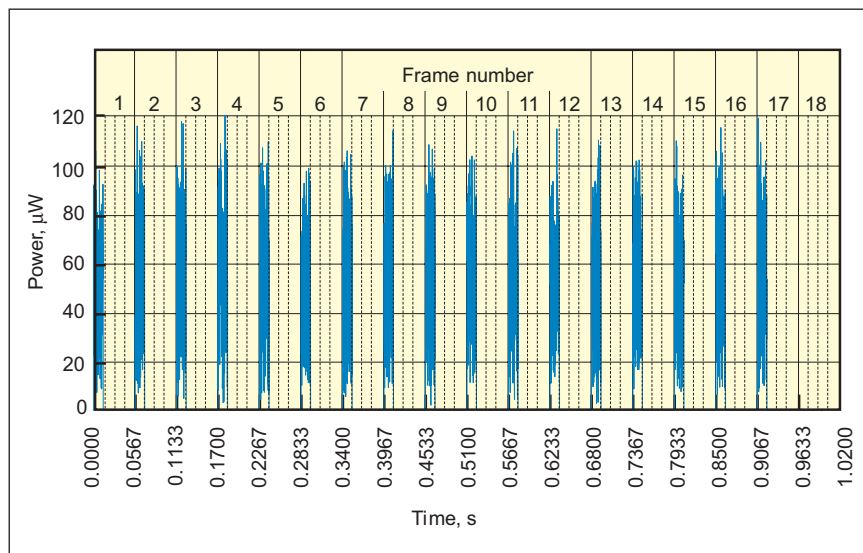
Measurement system

- 54 A Simoco Digital Systems SRP1000 TETRA hand portable was used to produce signals typical of those from TETRA mobile terminals used in Trunked Mode Operation (TMO). The hand portable was connected directly to a Simoco base station via attenuators and a T-piece connector. This allowed the signals exchanged between the two to be observed with the same spectrum analyser used for the base station measurements in the previous section.
- 55 The spectrum analyser was set up in the same way as for the base station measurements except for the sweep time, which was set to be over one complete multiframe, ie 1.02 s. This longer sweep time was needed to cover periodicities in the time domain signal, which occur over a multiframe and affect the power modulation spectrum significantly. These settings resulted in a sampling interval of 125 μ s and therefore only allowed one sample to be taken every 2.2 modulation symbols.
- 56 Using the spectrum analyser in the above way would result in samples with the same overall statistical distribution of power as if a shorter sampling interval had been used, although it would not be possible to follow the power evolution continuously over time by interpolation between the samples.

Time domain results

- 57 The output power waveform from the hand portable is shown in Figure 11. The major x-axis gridlines are aligned to the frame boundaries and the minor gridlines are aligned to the timeslot boundaries.
- 58 The figure shows that the hand portable transmits discontinuously with a single burst occupying timeslot 1 of frames 1-17. The burst is, however, missed out in frame 18, which is the control frame (see Figure 4). This indicates a theoretical duty factor of 23.61% for mobile terminals operating in TMO, if the burst-averaged output power were to be maintained over the full duration of each occupied timeslot and instantly fall to zero outside the timeslot.

FIGURE 11 Output power waveform over one multiframe for a TETRA mobile terminal transmitting in TMO



59 In practice, TETRA mobile terminals transmitting normal uplink bursts in only one timeslot are required to ramp up their power within a period of 16 symbols at the beginning of the timeslot and then down again within a period of 15 symbols at the end of the timeslot (ETSI, 2000: Section 6.4.5). Mobile terminals would therefore have a slightly lower duty factor than that indicated above.

Frequency domain results

60 The basic time domain dataset with 8192 samples covering a period of 1.02 s and used to plot Figure 11 was taken to be one complete cycle of the waveform and therefore was used as a complete dataset for spectral analysis. This basic dataset was concatenated 32 times in order to improve the frequency resolution in its Fourier transform. The input dataset therefore had 262 144 ($= 2^{18}$) samples and covered a total time of 32.64 s. A Hann window was applied to the input data and the bin separation in the resulting transform was 0.0306 Hz.

61 The burst-averaged power of the hand portable signal was calculated as the average power over the *useful* part of the burst in each of the 17 occurrences of transmission timeslot 1. Figure 5 shows that this useful part of normal uplink bursts contains bits 39–492 because the remaining time is allocated to guard periods and tail bits. The output from the Fourier transform was normalised to the burst-averaged power and the results are shown in Figure 12.

62 The time-averaged power of the handset signal is 12.42 μW and the burst-averaged power is 57.59 μW , indicating that the duty factor is 21.56%.

63 The time domain graph (Figure 11) clearly shows that the output power from the mobile terminal was in the form of a train of pulses and this is also evident from its spectrum. The 17.64 Hz harmonic was the strongest component in the spectrum and had a coefficient equal to 39.5% of the burst-averaged power, or 183% of the time-averaged power. Subsequently there are odd and even harmonics of 17.64 Hz with progressively decreasing amplitude.

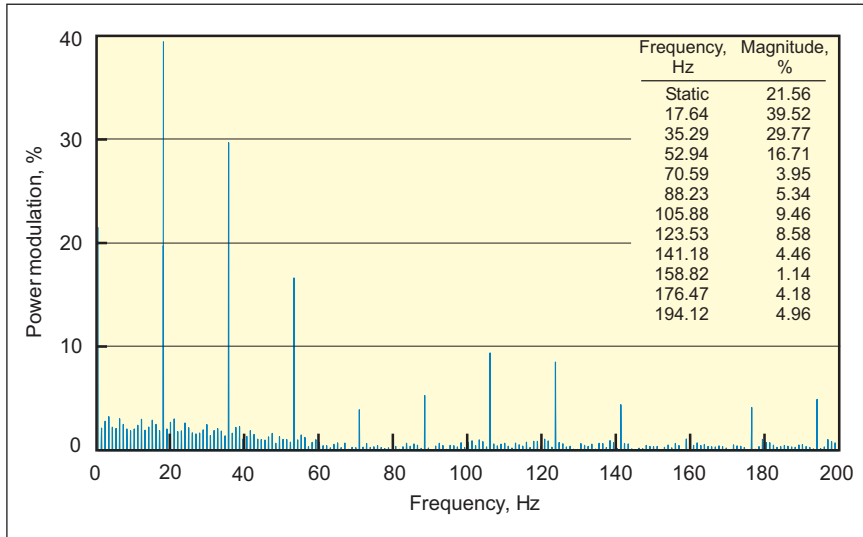


FIGURE 12 Power modulation spectrum for the output signal from a TETRA mobile terminal transmitting in TMO

- 64 The spectrum also shows harmonics of 0.98 Hz which imply cyclical power variations over the multiframe period of 1.02 s. These arise because the 18th burst is omitted from every frame.
- 65 It has already been observed that using the 125 μ s time domain sampling interval does not allow the waveform power evolution to be followed continuously over time and this also has implications for the Fourier transform. With this sampling interval, the Nyquist frequency is 4 kHz, which is still very much higher than the power modulation frequencies of interest to this work, although it is below the symbol rate of 18 kHz. Power modulation at frequencies higher than the 4 kHz Nyquist frequency, eg at the symbol rate, will have been *aliased* into the Fourier transform below the Nyquist frequency. Appendix C considers this effect further and shows that the uncertainty introduced to the spectral coefficients is negligible.
- 66 Although the results in this section were obtained for a particular TETRA mobile terminal, the power modulation observed arises from aspects of the signal that are integral to the TETRA standard. Similar results would therefore be found for any other TETRA mobile terminal operating in TMO.

MOBILE TERMINAL SIGNALS IN DIRECT MODE OPERATION

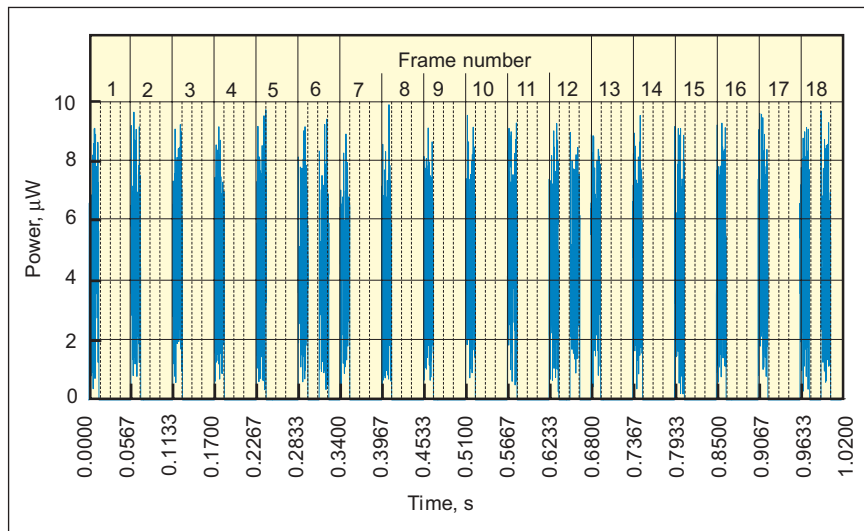
Measurement system

- 67 A Simoco Digital Systems SRP1000 TETRA hand portable was used to produce signals typical of those from TETRA mobile terminals in Direct Mode Operation (DMO). The hand portable was connected directly to another mobile terminal via attenuators and a T-piece connector allowing the signals exchanged between the two to be observed with the spectrum analyser. The settings of the spectrum analyser were exactly the same as for the measurements in TMO and so the comments made in paragraphs 56 and 65 about under-sampling the waveform and its effect on the Fourier transform apply equally here (see Appendix C).

Time domain results

- 68** The output power waveform from the hand portable is shown in Figure 13. The major x-axis gridlines are aligned to the frame boundaries and the minor gridlines are aligned to the timeslot boundaries.
- 69** The figure shows that the hand portable transmits discontinuously with a single burst occupying timeslot 1 of all 18 frames; however, bursts are also transmitted in timeslot 3 of frames 6, 12 and 18. This indicates a theoretical duty factor of 29.17% for mobile terminals operating in DMO. This, however, assumes that the burst-averaged output power is maintained over the full duration of each occupied timeslot and instantly falls to zero outside the timeslot which would not be the case in practice for the reasons given in paragraph 59.
- 70** The technical standard (ETSI 1998, Section 4.3.2) explains the signalling protocol and indicates that the timeslot 1 bursts are normal discontinuous downlink bursts and the timeslot 3 bursts are synchronisation discontinuous downlink bursts, as shown in Figure 5.

FIGURE 13 Output power waveform over one multiframe for a TETRA mobile terminal transmitting in DMO



Frequency domain results

- 71** The approach used to Fourier transform the DMO data was the same as that for the TMO data in paragraph 60. The burst-averaged power of the signal was assumed to be the average power over the useful part of the bursts occurring in timeslots 1 and 3 and the resulting normalised transform is shown in Figure 14.
- 72** The time domain graph shows that the output power from the mobile terminal occurs in a train of pulses, although their spacing is not as regular as in the TMO waveform because of the timeslot 3 pulses in every 6th frame. Harmonics of 17.64 Hz feature strongly in the spectrum, although in contrast with TMO, it is the second harmonic at 35.29 Hz that is the strongest. This is because the timeslot 3 pulses cause the waveform to have some periodic character over intervals corresponding to two timeslots.

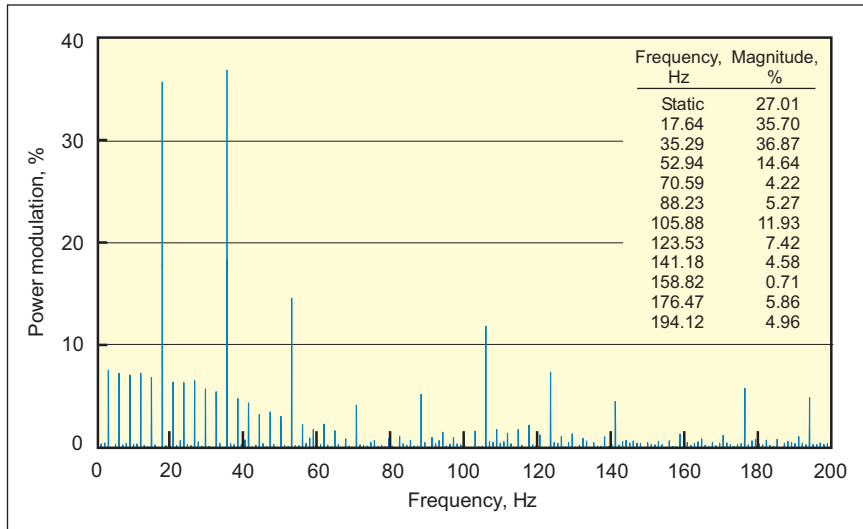


FIGURE 14 Power modulation spectrum for the output signal from a TETRA mobile terminal transmitting in DMO

- 73 The spectrum also shows harmonics of 2.94 Hz and these arise because of the periodicity of the waveform over intervals of six timeslots, ie 340 ms.
- 74 The time-averaged power of the handset signal is 1.334 mW and the burst-averaged power is 4.943 mW, indicating that the duty factor is 27.00% and so somewhat higher than the 21.56% found in TMO.
- 75 Although the results in this section were obtained for a particular TETRA mobile terminal, the power modulation observed arises from aspects of the signal that are integral to the TETRA standard. Similar results would therefore be found for any other TETRA mobile terminal operating in DMO.

SUMMARY AND CONCLUSIONS

- 76 Waveform measurements indicate that, to within experimental precision of less than 1%, TETRA base station signals are continuous and not pulsed over time intervals that could cause power modulation at frequencies between 1 and 200 Hz. This conclusion is consistent with the TETRA technical standard and with information obtained during detailed discussions with network operators and system manufacturers.
- 77 Although TETRA uses phase modulation to encode data on to its radio signals, the transmitted signals normally exhibit significant amplitude (and hence electric field) variations, because of the filtering that is applied after modulation. The power histogram contains amplitude samples up to 70% greater than the mean amplitude, although the average amplitude is essentially constant over time intervals comparable to or larger than the timeslots. Another source of power modulation could arise under certain conditions, for example when there is little call traffic, the amplitude variations in base station signals can cease for periods of 1.78 ms in some or all of the 14.17 ms timeslots. However, the TETRA system is designed to ensure that the power emitted during these constant amplitude periods is the same as the average power at other times.

78 Power modulation does occur in the transmission from Dolphin and Simoco base stations at a very low frequency of 0.245 Hz. This arises from the 6 ms breaks in the transmission at 4.08 s intervals when the base station power amplifiers carry out linearisation. This does not occur, however, in the transmission from BT Airwave base stations.

79 The power modulation content of the measured TETRA waveforms was obtained by Fourier analysis and the harmonic coefficients derived for the various transmitters considered during this work are summarised in Table 2. Two figures are given for each base station's harmonic coefficients: one assuming that there is no break in transmission while the amplifier is linearised (no BLCH) and one with a 6 ms break in transmission every 4.08 s (BLCH). Only one of these conditions would occur with each real base station and so the numbers relating to the other (hypothetical) condition are shown in brackets.

TABLE 2 Summary of power modulation harmonic coefficients for TETRA base station and mobile terminal waveforms

Transmitter		Duty factor (%)	Harmonic coefficients (%)			
			17.64 Hz	35.29 Hz	52.94 Hz	70.59 Hz
Simoco BS (Simoco)	BLCH	99.85	0.327	0.229	0.203	0.402
	No BLCH	(100)	(0.070)	(0.100)	(0.062)	(0.202)
Nokia BS (Dolphin)	BLCH	99.85	0.930	0.532	0.171	1.071
	No BLCH	(100)	(0.564)	(0.246)	(0.204)	(0.866)
Motorola BS (Airwave)	BLCH	(99.85)	(0.707)	(0.571)	(0.204)	(1.001)
	No BLCH	100	0.417	0.434	0.448	0.785
Mobile (Simoco SRP1000)	TMO	21.56	39.52	29.77	16.71	3.95
Mobile (Simoco SRP1000)	DMO	27.00	35.7	36.9	14.64	4.22

80 The power modulation coefficients for the measured base station signals are around 1% or less of the average waveform power. Since, however, coefficients of comparable size to these can be shown to arise from statistical fluctuations associated with the limited number of samples taken, it is not possible to conclude from this work that TETRA signals from base stations have any power modulation other than that at 0.25 Hz. It is not possible to rule out power modulation at levels less than these. It is also important to note that the use of inappropriate experimental procedures can result in erroneous power modulation coefficients larger than those reported here.

81 The waveforms from TETRA mobile terminals are not continuous since bursts are used with the power ramped up at the beginning and then down at the end of each timeslot. The precise shape of the power modulation spectrum obtained with mobile terminals depends on which timeslots are being used, but 17.64 Hz and its harmonics dominate for the TMO and DMO transmissions considered in this work.

82 Power modulation coefficients up to 40% of the burst-averaged power were found in signals from the mobile terminals measured in this work. These arise from signal features that are an integral part of the TETRA standard and so coefficients of similar size should be present in the signals from all TETRA mobile terminals.

Acknowledgements

- 83** NRPB would like to acknowledge the support of Simoco Digital Systems and the staff at its Cambridge site during the preparation of this Technical Note. In particular, thanks are due to John Wilson for his comments and help with the TETRA technical standard. Thanks are also due to BT Airwave and Dolphin Telecom for providing information about their radio sites.
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Appendix A

DIGITAL MODULATION OF RADIO SIGNALS

This appendix reviews analogue and digital modulation schemes and provides background information and terminology. It also examines and defines the meaning of power modulation and pulse modulation when applied to modulated radio signals.

Analogue modulation schemes

The principle of analogue modulation schemes is to produce a signal at a suitable frequency for transmission, known as the carrier signal and then to vary some aspect of this carrier signal in response to the amplitude of a lower frequency signal, known as the baseband signal. Analogue modulation schemes usually fall into one of the two basic categories shown in Figure A1.

With amplitude modulation (AM), the amplitude of the carrier signal is made proportional to the amplitude of the baseband signal, whereas with phase modulation (PM), the phase of the carrier signal is made proportional. Changes in carrier phase result in changes in frequency and so phase modulation is normally known as frequency modulation (FM) in analogue systems.

Digital modulation

Instead of allowing continuous variations of the carrier amplitude or phase in response to an analogue baseband waveform, digital modulation schemes either discretise the amplitude, the phase, or both the amplitude and the phase of the carrier into a number of defined states. The modulated signal then moves between these states in response to a digital representation of the baseband signal. Two simple examples of digital modulation schemes are shown in Figure A2.

Amplitude shift keying (ASK) is similar to analogue amplitude modulation in that the amplitude of a carrier signal is varied while its frequency remains constant. In the example shown in Figure A2, there are only two possible carrier amplitudes – carrier on and carrier off – and the shifts between them are instantaneous. ASK schemes can use more than two discrete amplitude levels in their coding schemes and, in practice it takes a certain amount of time to switch from one state to the next.

Phase shift keying (PSK) involves changing the phase of the modulated carrier in relation to the unmodulated carrier, which is regarded as a reference signal. In the example shown in Figure A2, the phase of the modulated signal can be either 0° or 180° and changes between these two phase states are accomplished instantaneously. Practical PSK systems may use more than two phase states, and they will also take a certain amount of time to switch between states.

Changes in the phase of a modulated signal can be accomplished by either raising or lowering its frequency slightly so that a required phase change is accomplished over some desired period of time; for example, the modulation interval (shown in Figure A2). In this way, the signals used in PSK can resemble the signals produced in analogue frequency modulation systems.

It can be seen that, when an abrupt 180° phase shift takes place, there is no change in the amplitude of the modulated signal, S_m , but its slope, dS_m/dt , changes

discontinuously. To represent such a sharp feature requires a broad spectrum of frequencies and hence a wide frequency channel for its transmission, which would be an inefficient use of radio spectrum. Practical digital modulation schemes avoid sharp changes in signal magnitude and phase by spreading changes over each modulation interval in a way that minimises spectral requirements.

One important advantage of PSK over ASK is that it involves a constant transmitted power, and therefore represents a more efficient use of amplifier hardware and the radio spectrum. It should be noted that signal power is proportional to the amplitude squared.

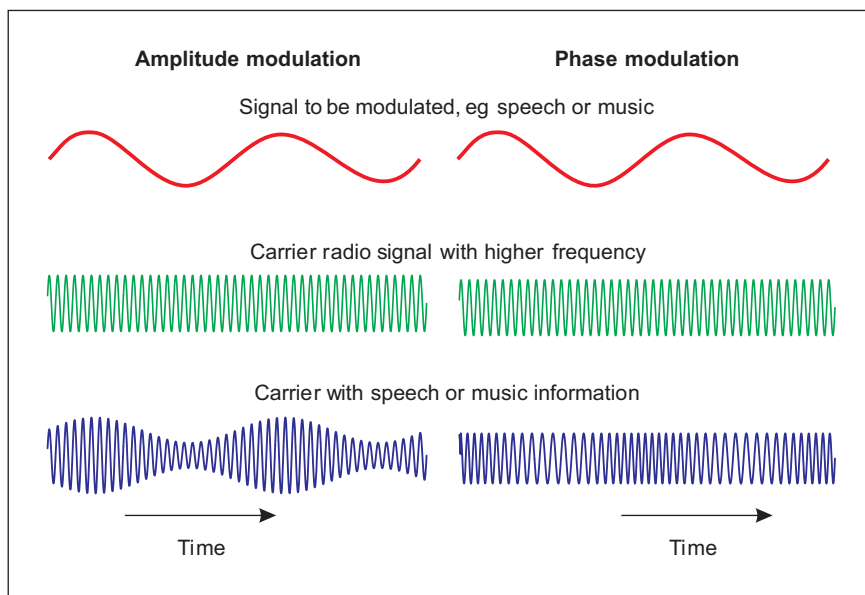


FIGURE A1 Analogue modulation schemes based on amplitude (left) and phase (right) modulation

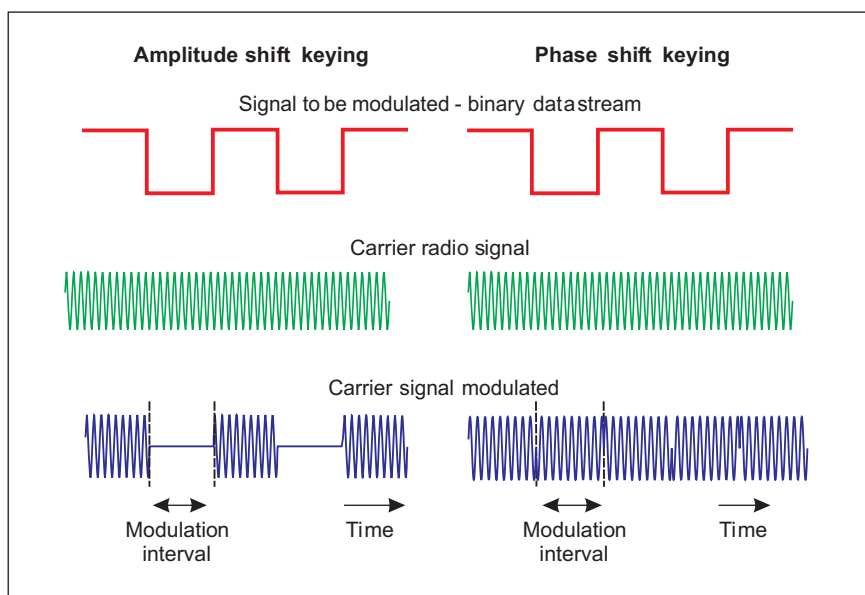


FIGURE A2 Amplitude shift keying (ASK) and phase shift keying (PSK) used to modulate a binary datastream on to a radio carrier signal

Symbols and constellation charts

It has been explained above that the signals produced in digital modulation schemes have a number of discrete states in relation to an unmodulated reference carrier. The states are characterised in terms of their magnitude and phase in relation to the reference and they can be represented on constellation charts, as shown in Figure A3.

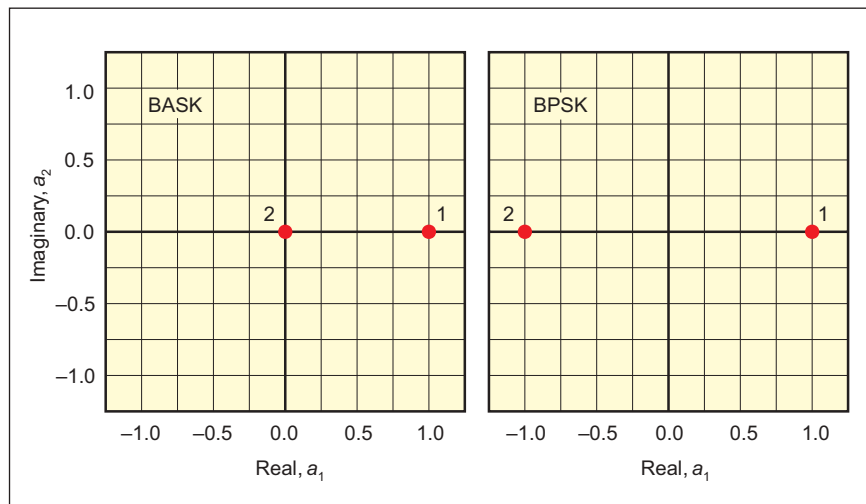
For digital modulation schemes that are not differential (see next section), the code states are known as *symbols* because each one symbolises a portion of the binary datastream. The BASK and BPSK examples used in this appendix are described as binary modulation schemes because they both only use two symbols (shown in Figure A3) and thus each symbol can only represent one bit of binary data. Modulation schemes that use more than two symbols can represent more than one binary digit with each symbol.

The linear distance from the centre of a constellation chart to a symbol represents the relative amplitude of the signal and the angular distance from the positive x -axis represents its relative phase. In this way, the x - and y -axes in a constellation chart represent the real and imaginary components of the complex number $a^* = a \exp(j\theta)$, where a is the signal magnitude and θ is its phase. The real component, $a_1 = a \cos \theta$ and the imaginary component $a_2 = a \sin \theta$.

For the BASK and BPSK examples shown above, it was assumed that a signal can move instantly from one state to another; however, real systems will always involve progressive changes in state over time. It is possible to parameterise the real and imaginary components of a^* as functions of time so that a trajectory can be plotted on a constellation chart showing how the signal moves from state to state. This trajectory can reveal whether a phase modulation scheme involves an amount of amplitude modulation, or vice versa.

Pure phase variations in a modulation scheme will produce a trajectory that follows a unit radius circle in the constellation chart, whereas pure amplitude variations will produce a trajectory that lies on the real axis. An example of the relevance of this can be

FIGURE A3
Constellation charts
for the binary ASK
and PSK modulation
schemes
considered in
Figure A2



demonstrated by considering the BPSK scheme in Figure A3 with a transition from state 1 to state 2. This transition can be accomplished in three different ways.

- (a) The frequency could be raised slightly so that the phase advances in an anti-clockwise direction around a circular trajectory.
- (b) The frequency could be lowered slightly so that the phase advances in a clockwise direction around a circular trajectory.
- (c) The amplitude could be reduced to zero and then increased again to form an inverted waveform. This would imply movement directly along the real axis.

Methods (a) and (b) for accomplishing the transition would require no change in the waveform power because the amplitude would remain constant, whereas method (c) would reduce the waveform power to zero midway through the transition. Finally, it should be noted that a trajectory plotted on a constellation chart does not reveal how quickly a transition occurs.

Differential phase modulation schemes

The phase modulation examples described above use the absolute phase of a modulated signal in relation to a notional reference carrier in order to represent portions of a binary datastream. With differential modulation schemes, it is the *change* in phase over each modulation interval that is used to represent a portion of the binary datastream.

A variant on the BPSK modulation scheme discussed above and which can be used as an example is differential BPSK. In DBPSK, a 0-bit in the datastream would cause a phase advance of 90° over the next modulation interval, whereas a 1-bit in the datastream would cause a phase retardation of 90° over the next modulation period. In this way the two symbols used in the scheme would be $+90^\circ$ and -90° phase changes, although there would be four code states revealed on a constellation chart at $(1+j0)$, $(0+j1)$, $(-1+j0)$ and $(0-j1)$. An example of DBPSK modulation is shown in Figure A4.

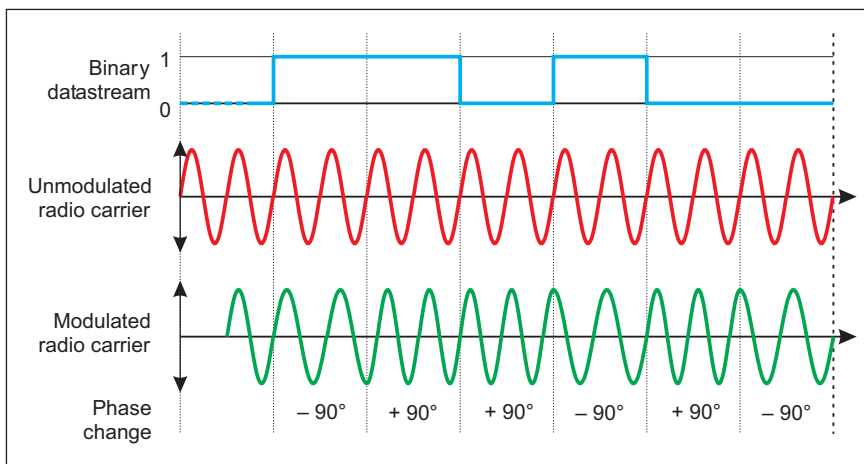
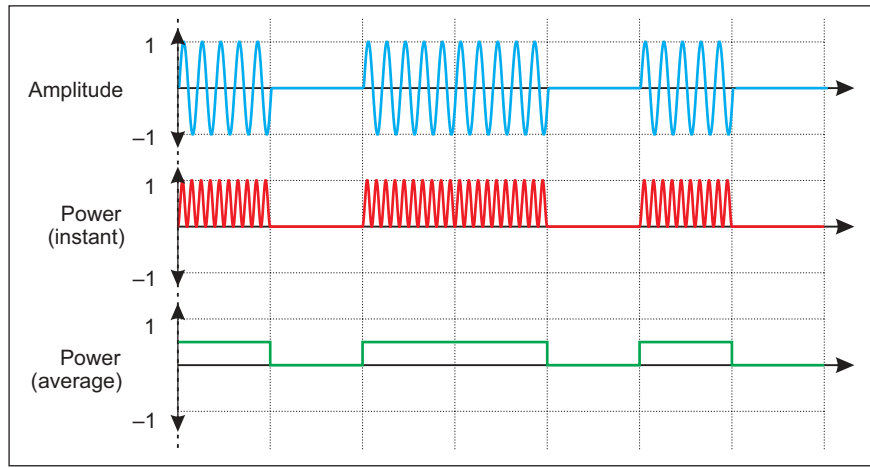


FIGURE A4
Differential Binary
Phase Shift Keying
(DBPSK)
modulation applied
to a radio carrier

Power terminology and modulation

As has been mentioned above, the power of a signal is proportional to its amplitude squared. It therefore follows that the *instantaneous power* of a signal whose amplitude varies sinusoidally with time also varies sinusoidally with time, but at twice the frequency of the signal amplitude and raised so that power remains positive. This is shown in Figure A5 and is a consequence of the trigonometric identity $\cos^2(\omega t) = \frac{1}{2}[1 + \cos(2\omega t)]$.

FIGURE A5
Variations in the
instantaneous power
and the average
power of a BASK
waveform over time



This work is concerned with slow systematic variations in the power of a radio signal that may be detected as a low frequency (less than 1 kHz) signal through some form of non-linear or rectification process. For this work, the average power of the radio signal over each complete sinusoidal oscillation of its radio carrier will therefore be taken as the power function to be analysed. This power function is shown in Figure A5 and the variations it exhibits over time are described as *power modulation*.

Power modulation can be essentially random or it may have a systematic structure with regular periodic variations over time. Fourier analysis can be used to analyse the measured power function of a waveform and identify any characteristic modulating frequency components that may be present. The magnitude of the harmonic coefficients in the spectrum quantifies the amount of each modulating frequency component that is present.

As an example, consider a square wave oscillating between the amplitude states +1 and 0 at a frequency, f_m , and with a 25% duty factor. The Fourier series representation of this square wave is as follows.

$$f(t) = \frac{1}{4} + \sum_{i=1}^{\infty} \frac{2}{i\pi} \sin\left(\frac{i\pi}{4}\right) \cos(i\omega_m t)$$

where ω_m is the angular frequency of the square wave and equal to $2\pi f_m$.

Now consider a sinusoidal radio frequency carrier of power, P_0 , that is switched on and off by the above square wave, ie modulated into pulses. The power of the radio carrier over time, $P(t)$, will thus be as follows.

$$P(t) = P_0 \left[\frac{1}{4} + \sum_{i=1}^{\infty} \frac{2}{i\pi} \sin\left(\frac{i\pi}{4}\right) \cos(i\omega_m t) \right]$$

P_0 is the average power while the carrier is switched on and it will be termed the *burst-averaged power* in this work.

The *time-averaged power* will also be referred to in this Technical Note and this is the average power of a signal over a period of time that is long in relation to any periodic variations in the signal power. This period is four multiframe in the case of TETRA base stations and one multiframe in the case of TETRA mobile terminals for the reasons given in the relevant results sections of the main report.

The term *peak power* is not used in this Technical Note, but it is defined as the maximum power while the carrier is switched on taking into account any amplitude modulation component. Generally the peak power of a TETRA signal is around 3.2 dB higher than the burst-averaged power.

The *power modulating function* is the ratio $P(t)/P_0$ and it has the harmonic coefficients shown in the table for the 25% duty factor square wave. It should be noted that the static term represents the average power of the signal over a complete period of the power modulation and it is equal to $\frac{1}{4}$ because of the 25% duty factor of the square wave.

Harmonic	Coefficient
Static	0.2500
First	0.4502
Second	0.3183
Third	0.1501
Fourth	0.0000
Fifth	-0.0900
etc	

Power modulation spectrum coefficients for a radio frequency signal power modulated by a 25% duty factor square wave

With more general waveforms modulating the power of a radio signal, the Fourier spectrum will have non-zero even harmonic coefficients and all of the harmonic coefficients will be complex numbers.

It is possible to normalise each of the harmonic amplitudes to the peak power of the waveform in order to express each harmonic as a percentage of the peak signal power and this is the approach taken in this Technical Note.

Appendix B

STATISTICAL FLUCTUATIONS IN THE BASE STATION SPECTRA

The analysis in the main report of the measured variation in power from a base station indicated that around 99.8% of power emitted was static, ie unmodulated, and that the Fourier coefficients of the components modulated at frequencies between 1 and 200 Hz were less than 1% of the time-averaged power. In this appendix, the uncertainties in the Fourier coefficients that arise from the measurement technique are considered.

Consider the experimental error that would arise in the Fourier coefficient at 17.64 Hz if measurements were made on a constructed signal that varies in a similar way with time to the sampled signal shown in Figure 7 of the main report. However, in contrast to the signal in Figure 7, let the constructed signal have a mean power that is the same for each occurrence of a particular timeslot number. Also, let the samples in the timeslots of the constructed signal be normally distributed.

As with the measured signal, 1024 samples are taken in each timeslot of the constructed signal and data are produced over two frames so that 2048 samples in total correspond to each timeslot. An indication of the Fourier coefficient at 17.64 Hz that would arise in the constructed signal, given the finite number of samples, is obtained by replacing the power samples in timeslots 1 and 2 by their respective mean values, \bar{P}_1 and \bar{P}_2 . The power samples in timeslots 3 and 4 are then also taken to be equal to \bar{P}_2 .

If \bar{P}_2 is equal to the true average signal power, then for the normal distribution there is a 68% chance that \bar{P}_1 would differ from \bar{P}_2 by an amount less than the *standard error of the mean* power for the samples in timeslot 1, Π_1 , where

$$\Pi_1 = \frac{\sigma_1}{\sqrt{n}}$$

n is the number of timeslot 1 samples (= 2048) and σ_1 is their standard deviation, as given by

$$\sigma_1 = \sqrt{\frac{\sum_{j=1}^n (P_j - \bar{P}_1)^2}{n-1}}$$

in which P_j are the power samples in timeslot 1. For the data in Figure 7, $\sigma_1 = 4.58$ mW and $\bar{P}_1 = 9.96$ mW so $\Pi_1 = 0.101$ mW. Now there is then a 68% chance that \bar{P}_1 will not differ from \bar{P}_2 by an amount greater than Π_1 / \bar{P}_1 , ie 1.0%.

The model signal can therefore be separated into a constant term $1 - \Pi / \bar{P}_1$ plus a square wave which oscillates between the amplitude states Π / \bar{P}_1 and 0 with a 25% duty cycle. From the analysis in Appendix A, this leads to a Fourier coefficient for 17.64 Hz power modulation of $0.45\Pi / \bar{P}_1$ around 0.45%. This is comparable to the values for the Fourier coefficient obtained from the measured data.

Appendix C

EFFECT OF ALIASING ON THE MOBILE TERMINAL SPECTRA

In the main text, it has been noted that the waveform from the mobile terminal is not sampled at sufficiently short time intervals to follow the signal evolution continuously in the time domain. This implies that the Fourier transform of the sampled data cannot extend up to a sufficiently high frequency to encompass all of the signal power and it gives rise to *aliasing* of the power at frequencies beyond the resolved part of the spectrum. This appendix considers the extent to which aliasing occurs and its effect on the power modulation coefficients reported for harmonics of 17.6 Hz with mobile terminals.

The Fourier transform only extends up to the Nyquist frequency of 4 kHz in the mobile terminal power modulation spectra derived in the main report (see Figures 12 and 14), whereas the power modulation must extend above the symbol rate of 18 kHz. The effect of aliasing is to move the power in the signal at frequencies above the Nyquist frequency into the spectrum below the Nyquist frequency in a systematic way. If the form of the spectrum above the Nyquist frequency is known, it is possible to predict the way in which the aliasing occurs and assess the effect on the spectrum coefficients below the Nyquist frequency, as follows.

The power modulation spectrum for mobile terminals at frequencies around 18 kHz will be very similar to that of base stations because they both use the same DQPSK modulation scheme, although the effect of the discontinuous nature of the mobile terminal waveform has to be considered. The analysis in this appendix therefore uses the frequency domain data for the base station to determine the effect of aliasing on the frequency domain data for the mobile terminals.

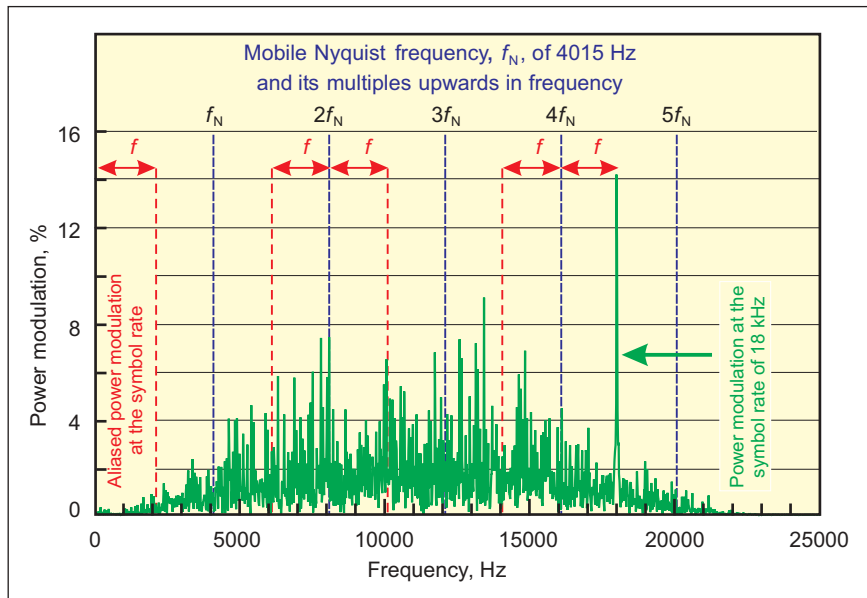
The base station waveform in Figure 7 of the main report is sampled at sufficiently short time intervals to produce its power modulation spectrum at frequencies up to a Nyquist frequency of 36 kHz, and so the spectrum extends considerably beyond the symbol rate. This is shown in the figure below, which is derived from the first frame of time domain data shown in Figure 6 of the main report, although no concatenation has been used so the transform is based on only 4096 samples and has a bin separation of 8.8 Hz.

The figure shows the 4 kHz Nyquist frequency achieved in transforming the mobile terminal time domain data and also its multiples at higher frequencies extending to encompass the power modulation evident. The base station power modulation spectrum at frequencies above 4 kHz includes a single bin peak of amplitude around 14% of the burst averaged power at 18 kHz, and this corresponds to the symbol rate. The spectrum also shows a broad spread of power modulation over all frequencies up to around 20 kHz and which generally rises to a peak of around 2% around 10 kHz, although some individual bins contain power modulation up to 9%.

The frequency offset, Δf , shown in the figure indicates how the power modulation at the symbol rate of 18 kHz is aliased below the Nyquist frequency of 4 kHz to a frequency of 2 kHz with the mobile terminal data. The power modulation will also

reduce in amplitude by a factor of around four due to the duty factor of the mobile terminal. A frequency of 2 kHz is well above the 17.6 Hz frequency and its first few harmonics that are of interest to this work and so aliasing of this aspect of the mobile terminal spectrum can be ignored when considering the power modulation coefficients in Figures 12 and 14 of the main report.

Power modulation spectrum derived from the base station time domain data showing how the power at the symbol rate of 18 kHz is aliased down in frequency for the mobile terminal



The broad spectrum of power modulation in the mobile terminal waveform at frequencies above 4 kHz will be aliased below this frequency in a fairly evenly distributed way, although the phase of the component entering each frequency bin cannot easily be determined. The magnitude of the coefficient typically entering each bin below 4 kHz can be determined by integrating the base station power modulation spectrum at frequencies above 4 kHz and then sharing the power modulation between the bins in the mobile terminal spectrum below 4 kHz.

Assuming, on a worst-case basis, that 100% of the power modulation in the base station signal is at frequencies above 4 kHz, implies that around 25% of the power modulation in the mobile terminal signal would be at frequencies above 4 kHz. This modulation would then be aliased down in frequency and divided between the 131 073 bins in the mobile terminal spectra of Figures 12 and 14 of the main report (up to 4 kHz). Hence, it would introduce an uncertainty of around 0.02%. This is a small amount in relation to the 17.6 Hz harmonic coefficients reported and so it can be neglected.