4

Radiofrequency Fields from Mobile Phone Technology

Radiofrequency Radiation Usage

4.1 Mobile phones and their base stations transmit and receive signals using electromagnetic waves (also referred to as electromagnetic radiation or fields, or radio waves). Electromagnetic radiation is emitted by many natural and man-made sources and plays a very important part in our lives. We are warmed by the radiation from the Sun or from an electric fire and we see using that part of the electromagnetic spectrum that our eyes can detect. All electromagnetic radiation consists of oscillating electric and magnetic fields and the frequency, f or ν (*nu*), which is the number of times per second at which the waves oscillate, determines their properties and the use that can be made of them. Frequencies are measured in hertz or Hz, where 1 Hz is one oscillation per second, 1 kHz or kilohertz is a thousand Hz, 1 MHz or megahertz is a million Hz, and 1 GHz or gigahertz is a thousand million Hz or 10^9 Hz. Frequencies between about 30 kHz and 300 GHz are widely used for telecommunication, including broadcast radio and television, and comprise the radiofrequency (RF) band.

4.2 In the UK, AM radio uses frequencies between about 180 kHz and 1.6 MHz, FM radio ranges from 88 to 108 MHz, and TV ranges from 470 to 854 MHz. Cellular mobile phone services operate within the frequency ranges 872–960 MHz and 1710–1875 MHz. Waves at higher frequencies but within the RF region, up to around 60 GHz, are referred to as *microwaves* and have a wide variety of uses. These include radar, telecommunications links, satellite communications, weather observations and medical diathermy; intense sources of 2.45 GHz microwaves confined within ovens are used for cooking. At even higher frequencies, radiation takes the form of infrared, then visible, ultraviolet, X-rays and eventually the γ-rays (*gamma* rays) emitted by radioactive material. Electromagnetic radiation is also characterised by its wavelength λ (*lambda*), which equals the velocity or speed of the wave (the speed of light) divided by its frequency.

Radiocommunication

4.3 An RF wave used for radiocommunication is referred to as a carrier wave. The information it carries – speech, computer data, etc – has to be added to the carrier wave in some way, a process known as modulation. The information can be transmitted in either analogue or digital form. For example, the electrical signal from a microphone produced by speech or music is an analogue signal at frequencies up to about 15 kHz. So the signal varies significantly with time on a scale of a few microseconds or μs (1 μs is a millionth of a second). At a particular time it might have any value within quite a large range. So if this signal is sent by analogue transmission, the size or amplitude of the RF carrier wave at any instant is made proportional to the size of the electrical modulating signal at that instant (this is called amplitude modulation and other forms of modulation can also be used) (Figure 4.1). The carrier wave varies very much faster than the signal so that the modulation produces a relatively slow oscillation in the amplitude of the carrier wave. Information can also be transmitted in digital form. In this case only a small number of symbols are used. Printed language is an example of digital information since it only uses the symbols of the alphabet. Morse code is another and only uses two symbols, dots and dashes, so is called a binary system. Analogue signals are described by a number, which in general is not an integer (whole number), and the first step in digitising it is to round this to the nearest integer. For example, if the strength of an electrical signal from a microphone at a particular instant is 12793.56 microvolts or µV (1 µV is a millionth of a volt) the number 12793.56 is rounded to 12794. This can then be expressed in binary form in which it is represented by a series of zeros and ones, and these can be transmitted digitally to a receiver that converts them back to a signal of strength 12794 µV. Digital transmission, usually binary, offers many technical advantages over analogue transmission systems. It is, for example, less susceptible to distortion by interference and electrical noise, and it is replacing or has replaced analogue transmission in radio, TV, mobile phones, etc.

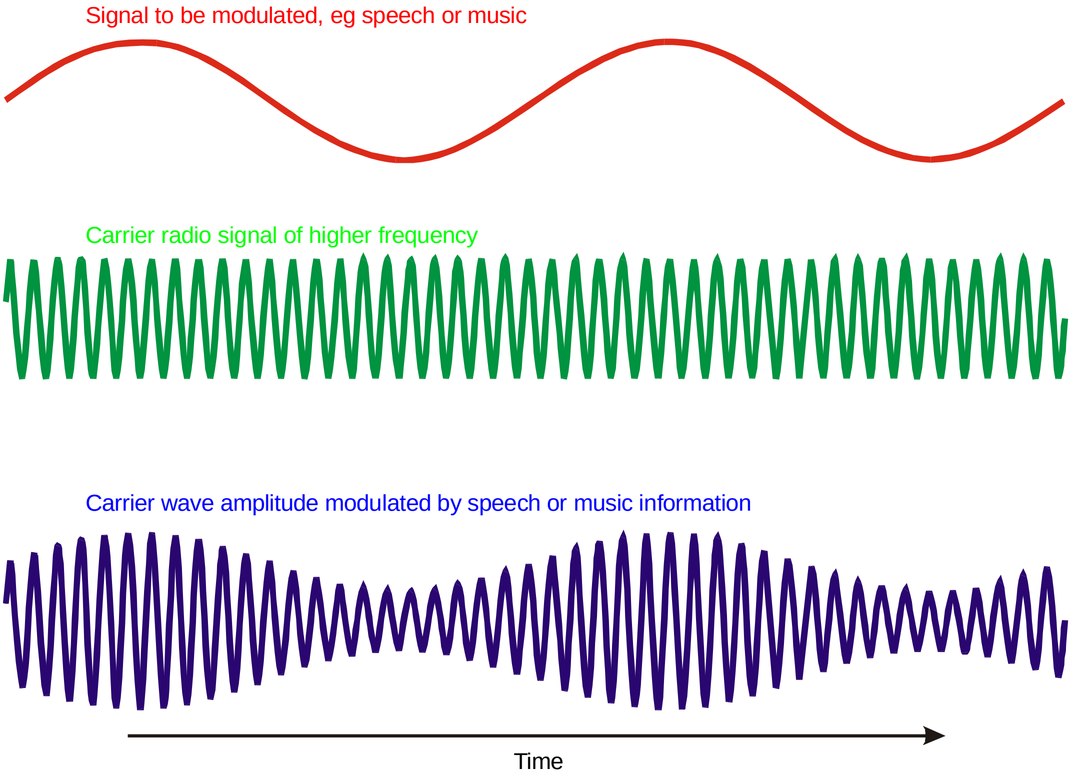

Figure 4.1 Amplitude modulation of a carrier wave

Electromagnetic Compatibility

4.4 The ability of electrical and electronic systems to operate in an electromagnetic environment without adverse effects is known as electromagnetic compatibility (EMC). The reality is that all electrical systems can be disturbed if subjected to sufficiently powerful emissions. For this reason, EMC is achieved by limiting or controlling electromagnetic emissions in addition to ensuring that electrical systems are sufficiently immune to electromagnetic interactions.

4.5 Mobile phones are intended to be electromagnetic emitters and as such their radiation characteristics (frequency, power, etc) are tightly regulated by standards set by organisations such as the European Telecommunications Standards Institute (ETSI). However, the distance between a mobile phone and an electrical system can vary considerably. A substantial research project recently concluded (DTI, 1999) that future mobile phone systems would have less adverse EMC effects than present systems, and suggested some techniques for reducing the effects still further.

4.6 EMC is of particular concern in hospitals because of the diversity of electronic equipment in use and safety-critical circumstances involved. The Medical Devices Agency issued a warning in 1994 and recommendations in 1997 (MDA, 1997) and many hospitals have imposed restrictions of varying degrees on the use of mobile phones in hospitals. Similarly, the use of mobile phones in aircraft is not permitted for EMC reasons.

4.7 EMC issues have not been considered in any detail as part of the work described in this Expert Group report.

Technology of Cellular Mobile Phones

Cellular radiofrequency networks

4.8 A mobile phone sends and receives information (voice messages, fax, computer data, etc) by radiocommunication. Radiofrequency signals are transmitted from the phone to the nearest base station and incoming signals are sent from the base station to the phone at a slightly different frequency. Once the signal reaches a base station it can be transmitted to the main telephone network, either by telephone cables or by higher frequency (such as 13, 23 or 38 GHz) radio links between an antenna (eg dish) at the base station and another at a terminal connected to the main telephone network. These microwave radio links operate at rather low power and with narrow beams in a direct line of sight between the antennas, so that any stray radiation from them is of much lower intensity than the lower frequency radiation transmitted to the phones (FEI, 2000)[*].

4.9 Signals to and from mobile phones are usually confined to distances somewhat beyond the line of sight. They can reach into buildings and around corners due to various processes including reflection and diffraction, that allows the radiation to bend round corners to some degree, but the coverage area from a base station is partly governed by its distance to the antenna’s horizon. In the current GSM system (see paragraph 4.11), a timing artefact in the signal processing within the receivers limits the maximum distance over which a mobile phone can be used to about 35 km (22 miles). For such reasons an extensive network of base stations is needed to ensure coverage throughout the UK. An ideal network may be envisaged as consisting of a mesh of hexagonal cells, each with a base station at its centre (Figure 4.2), but in practice the coverage of each cell will usually depart appreciably from this because of the topography of the ground and the availability of sites for the base stations. The sizes of the cells are usually less than the 35 km maximum because obstruction by hills, buildings and other ground features reduces the effective range. Frequencies are reused several cells away and the capacity of a network (the number of simultaneous phone calls which may be made) depends on the extent of the frequency spectrum available, the cell diameter and the ability of the system to work against a background of interference from other cells. To accommodate the steadily increasing volume of users, cell sizes have to be progressively reduced (for example, by using base station antennas of lower height and reduced power) so that the frequencies may be reused more often. Indeed in large cities, base stations may only be a few hundred metres apart. The 20,000 or so base stations in the UK

---

[*] The maximum intensity on the ground 15 m from an antenna of a microwave link is stated to be 45 $\mu W/m^2$.

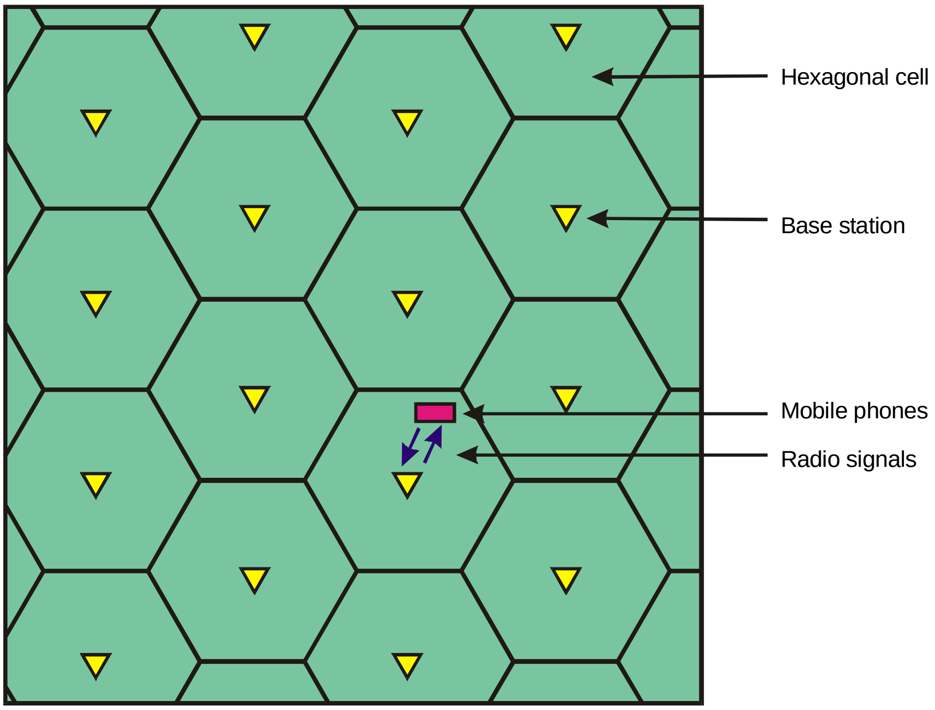

Figure 4.2 Network of base stations at the centre of hexagonal cells

mentioned in paragraph 2.14 each serve a “macrocell”. Additional, smaller base stations[*] operating over even shorter distances are being installed in places such as railway stations where the density of users is particularly large (“microcells”) and also within buildings such as office blocks (“picocells”). Cellular systems also include technology that ensures that the frequency channels employed by a user in a vehicle change automatically as the vehicle moves from one cell to the next.

Cellular phone technologies

TACS (analogue)

4.10 The first cellular system employed in the UK was the analogue TACS (Total Access Communication System) for which the phones have a nominal output of 0.63 W (FEI, 2000). This system is being phased out so that the frequency channels it uses around 900 MHz may be allocated to more recent systems. It uses frequency modulation[†] that results in only very small and essentially random changes in the amplitude of the carrier wave.

GSM (digital)

4.11 Systems using the TACS standard have largely, although not entirely, been replaced by the European digital phone standard, GSM, the acronym for Global System for Mobile Communications (Pederson and Anderson, 1999; Steele and Hanzo, 1999), and mostly operate in either the 900 MHz or 1800 MHz band. This standard is now widely used in many parts of the world. The digital processing uses phase modulation[‡] that again results in only very small and essentially random changes in the amplitude of the carrier wave.

---

[*] For indoor propagation, it is possible that “leaky feeders” consisting of specially constructed cables may be used as sources of low intensity radiation.

[†] In frequency modulation, the frequency of the carrier is varied by an amount proportional to the size of the modulating signal. The amplitude of the carrier wave is not changed.

[‡] Two electromagnetic waves may have exactly the same frequency but may be “out of phase”. This means that one wave is displaced from the other so that, for example, when one has its maximum positive value, the other has its maximum negative value. When a wave is phase modulated, each digit that is transmitted introduces a phase change in the carrier wave and the change produced by a one is different from that produced by a zero.

4.12 In the GSM system, each user requires a frequency channel of bandwidth 200 kHz so there is a maximum of 174 channels (175 minus one needed for technical reasons) within the 35 MHz bandwidth of the 900 MHz band and 374 within the 75 MHz width of the 1800 MHz band available for allocation to network operators. The channels are distributed across the cells in a way that allows neighbouring cells to operate at different frequencies to avoid interference. Cells are very often divided into three 120° sectors with different frequencies for each. These considerations limit the number of frequency channels available to users in a particular sector. Since the wavelengths at 900 MHz are twice as long as those at 1800 MHz, they are better at reaching the shielded regions behind buildings, etc, as a result of diffraction (bending). So, to obtain the same coverage, fewer base stations and hence fewer channels are needed at 900 MHz than at 1800 MHz. One 2 One and Orange were in fact allocated 150 channels within the 1800 MHz band, and BT Cellnet and Vodafone were allocated 113 channels within the 900 and 1800 MHz bands.

4.13 To increase the number of users that can communicate with a base station at the same time, a technique called Time Division Multiple Access (TDMA) is employed that allows each channel to be used by eight phones. This is achieved by compressing each 4.6 ms chunk of information to be transmitted into a burst or pulse 0.58 ms long (1 ms or millisecond is a thousandth of a second). So the phones and base stations transmit for 0.58 ms, every 4.6 ms, which results in a 217 Hz pulse modulation[*] or variation in their output (217 Hz = 1/4.6 ms). For technical reasons, there is, in fact, additional data compression which leads to the phones and base stations transmitting 25 pulses but omitting every 26th, and so on. This produces further pulse modulation of the power output at the lower frequency of 8.34 Hz (= 217 Hz/26). There is, however, no detectable amplitude modulation at the frequency of 271 kHz (every 4 μs) at which the individual digits (zeros or ones) are transmitted since, as noted earlier (paragraph 4.11), this leads to a negligible change in amplitude.

4.14 The maximum powers that GSM mobile phones are permitted to transmit by the present standards are 2 W (900 Hz) and 1 W (1800 Hz)[†]. However, because TDMA is used, the *average* powers transmitted by a phone are never more than one-eighth of these maximum values (0.25 W and 0.125 W, respectively) and are usually further reduced by a significant amount due to the effects of adaptive power control and discontinuous transmission. Adaptive power control (APC) means that the phone continually adjusts the power it transmits to the minimum needed for the base station to receive a clear signal. This can be less than the peak power by a factor of up to a thousand if the phone is near a base station, although the power is likely to be appreciably more than this in most situations. Discontinuous transmission (DTX) refers to the fact that the power is switched off when a user stops speaking either because he/she is listening or because neither user is speaking. So if each person in a conversation is speaking for about half the time, he/she is only exposed to fields from the phone for that half of the conversation. In summary, the largest output from a phone occurs if it is mainly used at large distances from the base station or shielded by

---

[*] Pulse modulation is equivalent to amplitude modulation by several frequencies at once. Thus pulse modulation at 217 Hz is equivalent to amplitude modulation at 217 Hz (23.4%), 434 Hz (21.6%), 651 Hz (18.9%), etc; the figure in brackets shows the modulation amplitude compared with that of the pulse. At 8.34 Hz, the frequencies and sizes of the amplitude modulation are 8.34 Hz (1%), 16.68 Hz (1%), 25.02 Hz (1%), etc.

[†] To allow for small variations in performance that occur when a batch of phones is produced, standards require these powers to be met to within ±78% (±2.5 dB; a change in power from P_1 to P_2 can be described as a change of 10 log(P_2/P_1) dB or decibels where the log is to base 10). Improvements in manufacturing techniques since the standards were set have, however, substantially reduced the variations in performance and it appears very unlikely that any of the more recently produced mobile phones would approach the upper limits allowed by the standards, particularly as an important aim of the manufacturers is to achieve the greatest possible battery life which requires the power used to be as small as possible. Advice from the Mobile Manufacturers Forum (an international association of seven major manufacturers) notes that members of the Forum are not aware of any phones operating above the standard. Nevertheless it seems possible that some older phones might still be in use whose maximum powers are 3.56 W (900 Hz) and 1.78 W (1800 Hz).

buildings, etc. In this situation, the *peak* powers could approach the values of 2 W (900 Hz) and 1 W (1800 Hz) and the *average* powers could approach the values of 0.25 W (900 Hz) and 0.125 W (1800 Hz).

UMTS/IMT-2000 (digital)

4.15 A third generation of mobile telecommunications technology has now been agreed and will be introduced in the next few years. In Europe this is called UMTS (Universal Mobile Telecommunication System) and worldwide it is known as IMT-2000 (International Mobile Telecommunications - 2000). The frequency bands identified for this system are 1885–2010 MHz and 2110–2200 MHz and the need for additional frequency spectrum to meet the future expected demand for capacity has also been recognised and will be debated at the World Radiocommunication Conference in May 2000. The specifications allow some choice in the modulation to be used but it is expected that the main choice will be CDMA (Code Division Multiple Access). The frequency channels will have 5 MHz bandwidths and, as in GSM, each can be used by a number of users at the same time. However, in CDMA, a transmission is “labelled” by a coding scheme that is different for each user. Since all the transmissions occur at the same time, the changes in amplitude of the carrier wave are essentially random (noise-like).

4.16 Two types of CDMA are likely to be implemented: FDD (Frequency Division Duplex), where separate 5 MHz channels are used for the two directions (to and from the mobile phone), and TDD (Time Division Duplex) where the same channel is used but in different time slots. Both types lead to pulse modulation because of the need to send regular commands from the base station to change the power level. In FDD the pulse frequency is 1600 Hz, while for TDD it can vary between 100 Hz and 800 Hz (Pederson and Anderson, 1999).

4.17 The expected demand for the use of UMTS both for speech and for data and Internet services is such that systems may be expected to employ macrocells and microcells, and also short-range picocells, to meet the various requirements for mobility and wide bandwidth services – for example, in the office environment.

DECT (digital)

4.18 Cordless phones are used at very short ranges between a base station located at the telephone socket outlet within the house or office and the cordless phone handset. Earlier cordless phones used analogue technology and are now being replaced by a digital system, DECT (Digital Enhanced Cordless Telecommunications) which has performance advantages in terms of privacy and protection against interference. DECT is now in widespread and increasing use and operates at similar frequencies, around 1850 MHz, to cellular mobile phones. There are ten channels with a spacing of 1.728 MHz. In each channel there are 24 time slots within a 10 ms frame and the transmission within a slot uses a form of frequency modulation. So a particular phone emits a pulse every 10 ms (100 Hz) during one of the time slots. Since the maximum power emitted is 250 mW, the average power emitted is about 10 mW. Possibly, DECT technology may form part of an overall UMTS system.

TETRA (digital)

4.19 The new TETRA (Terrestrial Enhanced Trunk Radio System) technology is not intended for public systems connected to the telephone network. It is designed for closed groups (eg for communication within an organisation or company) and is coming into use for the emergency services and some commercial applications. Frequency bands are available at about 400 MHz and 900 MHz. The modulation method is complex. The main features, however, are a 25 kHz band divided into four frequency channels, each of which is divided into 56.7 ms frames containing 4 time slots. So the transmission is pulsed at 17.6 Hz (1/56.7 ms).

Other radio systems

4.20 A modern environment contains many types of radiotransmitter. Broadcast radio and television transmitters usually have substantially higher powers than those of mobile phone base stations because they are designed to serve large areas of the countryside. For the same reason, their antennas are usually placed on taller masts located on higher ground at some distance from centres of population. Other high power transmitters are used for air traffic control and surveillance radar, which usually employ pulse modulation. Transmitters of much lower power, roughly comparable to those of the macrocell base station transmitters used in mobile telecommunications, are used for other communications purposes such as radiopaging and communications by the police, emergency services, local government, utility services, security personnel, amateur radio operators, and taxi services. They vary widely in the type of coverage needed but a large number of transmitters is needed for many of the services because of their relatively low power outputs. So it is important to recognise that the exposure from mobile phone base stations is just one component of the total RF exposure that people receive. Indeed, the exposure received by people living near to broadcast transmitters of high power output is likely to be appreciably greater than that received by people living near to mobile phone base stations, although less than that from a mobile phone near to the body.

4.21 Individuals may also be exposed to radiation from nearby low power transmitting devices such as wireless burglar alarms, toys, baby alarms, microphones, theft protection devices and car door openers. All of these types of equipment are of such low power that they do not need individual spectrum licences.

4.22 There are also RF amplifiers, which are used in such a way that they are not intended to radiate. These include RF heating – for example, in the plastics industry – microwave diathermy in physiotherapy and microwave ovens. Some of these sources, such as industrial heat sealers and medical diathermy equipment, give rise to exposures to patients, workers and physicians that are far higher than those to the public from mobile phone base stations, although the exposures are for far less time.

Electric and Magnetic Fields, Intensities

4.23 An electromagnetic wave consists of electric and magnetic fields that oscillate between their peak (largest) values (positive and negative) and zero. The size of a field can be indicated either by the magnitude of the peak value or by an average value. Since the field is positive for half the time and negative for the other half, its mean value is zero. So the average used is the rms or root mean square value (the square root of the average of the square of the field) which is equal to the peak value divided by 1.4 ($\sqrt{2}$). All fields in this report are quoted in rms values unless otherwise indicated. The electric (E) fields are measured in volts per metre or V/m and the magnetic (B) fields (or magnetic flux densities) in tesla or T or, more usually, in mT (a thousandth of a tesla) or µT (a millionth of a tesla). (The magnetic H-field, measured in amperes per metre or A/m, is sometimes stated rather than the B-field. In the materials of interest here, an H-field of 1 A/m corresponds to a B-field of 1.3 µT.) If an electrically charged object such as an ion (an atom or group of atoms which has lost or gained one or more electrons) or a cell is exposed to an electric field, it feels a force of magnitude proportional to the field. If, however, it is exposed to a magnetic field it only feels a force if it is moving at an angle to the field. The size of the force is proportional to the magnetic field and to the speed at which the object is moving across the field. Magnetic fields can also interact strongly with magnetic material such as iron. The intensity I, or power density, of an electromagnetic wave is the power passing through 1 m^2, as illustrated in Figure 4.3. The power is usually measured in watts (W), milliwatts (mW) or microwatts (µW), where 1 W = 1,000 mW = 1,000,000 µW, and the intensity is measured in watts per square metre or W/m^2 (or in mW/m^2 or µW/m^2). Since the area of a sphere surrounding a source increases as the square of its radius, then in an ideal case (in the absence of any nearby objects including the ground) the intensity falls off as 1/(distance)^2, the inverse square law.

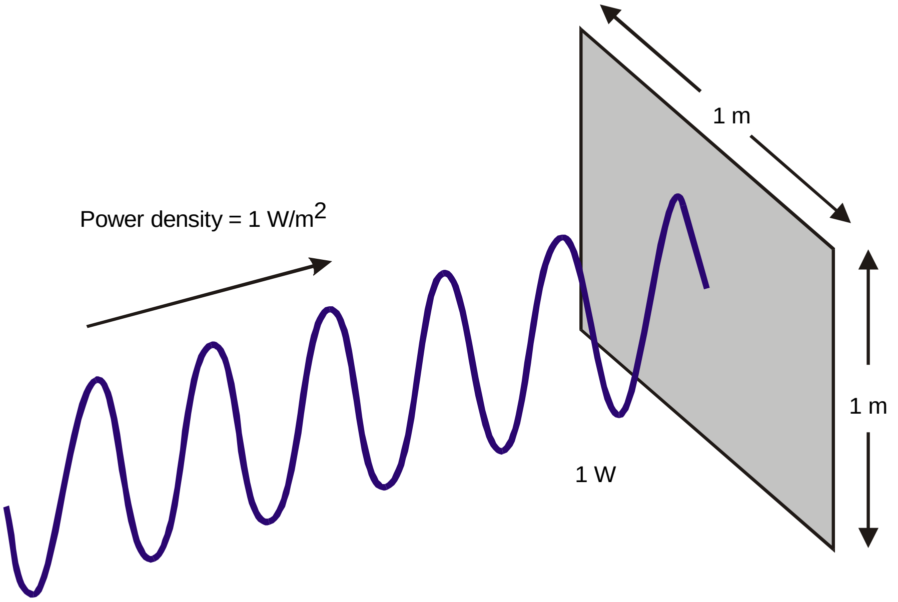

Figure 4.3 Electromagnetic wave passing through 1 m^2. If the power passing through the area is 1 W, the wave has an intensity or power density of 1 W/m^2

4.24 The properties of an electromagnetic field change with the distance from the source. They are simplest at distances of more than a few wavelengths – around a metre or more at the frequencies of interest here – which is referred to as the far-field region. In this region, the electromagnetic wave consists of an electric field E and a magnetic field B oscillating at right angles both to each other and to the direction in which the power of the wave is travelling (the direction of the intensity). The fields are in phase, so that the point at which E is greatest coincides with the point at which B is greatest, and their magnitudes are related to the intensity I (in W/m^2) by the expressions:

$$E = 19\sqrt{I}\ \text{V/m}$$

$$B = 0.06\sqrt{I}\ \mu\text{T}$$

4.25 In the near-field region, however, the situation is more complicated. The amount of power being radiated outwards is the same as that in the far-field region, but near to the antenna a considerable amount of electromagnetic energy is also being stored. So as well as the net radiated energy flowing outwards, there is additional energy that oscillates to and fro. These oscillating flows occur perpendicularly to the outward direction from the antenna as well as along it so the net energy flow is tilted with respect to the outward direction. The E-field and B-field are still at right angles to each other and to the direction in which the energy is being carried, but they are no longer in phase and their values can differ appreciably from the simple expressions that apply in the far-field region.

4.26 The difference in these properties near and far from an electric dipole antenna is illustrated in Figure 4.4, which shows the directions in which most of the energy flows. (The electric field directions are in the plane of the paper and perpendicular to the directions of energy flow, while the magnetic field directions are perpendicular to the paper.) Far from the antenna, the energy flows outwards. However, near to the antenna, most of the energy is stored around the antenna, flowing to and fro along its length, and only a small proportion is radiated outwards.

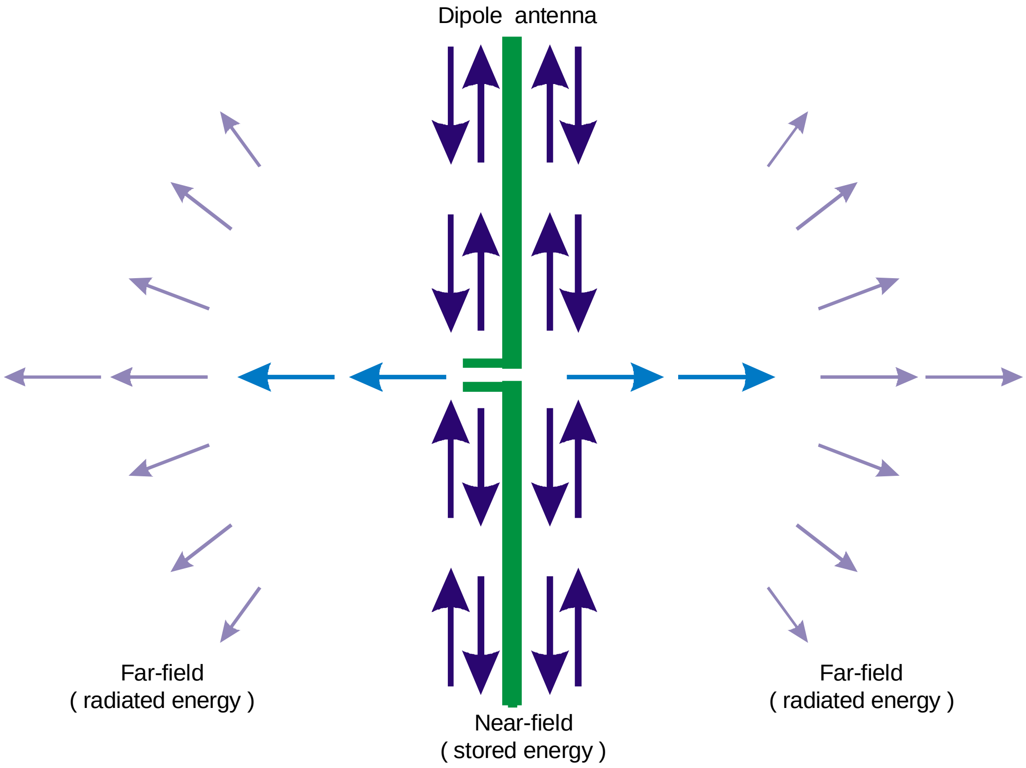

Figure 4.4 Electric dipole antenna showing the directions in which most of the electromagnetic energy flows

Fields from Mobile Phone Systems

4.27 The considerations in this section are restricted to the fields produced by GSM mobile phones and base station antennas since these form the large majority of those presently in use in the UK and Europe.

Output from mobile phones

4.28 The RF power from a phone is mainly transmitted by the antenna together with circuit elements inside the handset. The antenna is usually a metal helix or a metal rod a few centimetres long extending from the top of the phone. Neither type is strongly directional, although more power is radiated in some directions than others. At points 2.2 cm from an antenna (the distance at which calculations were made), the *maximum* values of the electric field are calculated to be about 400 V/m for a 2 W, 900 MHz phone and about 200 V/m for a 1 W, 1800 MHz phone and the *maximum* magnetic field is calculated to be about 1 μT for both phones*. For both 2 W, 900 MHz phones and 1 W, 1800 MHz phones the *maximum* intensity 2.2 cm from the antenna is very roughly about 200 W/m^2 (this is about one-quarter of the intensity of the Sun's radiation on a clear summer day, although the frequency of the emission from a phone is a million or so times smaller). These are the fields and intensities when the antenna is a long way from the head or body. When the antenna is near the body, the radiation penetrates it but the fields inside are significantly less, for the same antenna, than the values outside. For example, the largest *maximum* fields inside the head when its surface is 1.4 cm from the antenna are calculated to be about three times smaller than the values given above. (The *average* field values are all appreciably less than these *maximum* values for the reasons explained earlier.) As well as these RF fields, that are pulsed at 8.34 Hz and 217 Hz, there are magnetic fields near to the phone that oscillate at these same frequencies, and are a few μT in magnitude. These are generated by currents flowing from the battery which are switched on and off at these frequencies as a result of TDMA.

4.29 An indication of the size of these fields (although not of course any effect they may have) may be obtained by noting that the *maximum* values of these low and high frequency oscillating magnetic fields are about one-tenth the size or less of the Earth's static magnetic field, 50 μT, while the *maximum* values of the oscillating electric fields outside the body are a few times greater than the electric field at the surface of the Earth due to its static charge. This is directed towards the ground and on a fine day has a constant value of about 100 V/m.

Output from base stations

4.30 The base station antennas serving macrocells are either mounted on free-standing towers, typically 10–30 m high, on short towers on top of buildings, or attached to the side of buildings. In a typical arrangement, each tower supports three antennas, each transmitting into a 120° sector. A large proportion of the power is focussed into an approximately horizontal beam typically about 6° wide in the vertical direction and the rest goes into a series of weak beams (called side lobes) either side of the main beam. The main beam is tilted slightly downwards (Figure 4.5) but does not reach ground level until the distance from the tower is at least 50 m (usually 50–200 m).

4.31 The base station antennas transmit appreciably greater power than the phones. The limit to the power is formally set by the need to avoid RF interference and defined by a licence issued by the Radiocommunications Agency. This does not directly limit the total power emitted but does so indirectly by fixing the maximum intensity that an antenna can transmit into the main beam. This is done by defining the maximum "equivalent isotropically radiated power" (EIRP) that can be transmitted. The EIRP is the power that would have to be emitted equally in all directions to produce a particular intensity. In fact, as already noted, the antennas used are very far from isotropic, with most of the power being emitted into the main beam, and the ratio of the EIRP to the total power output is called the gain of the antenna. For a 120° sector antenna the gain is usually between about 40 and 60.

---

* It has already been noted that the electric and magnetic fields vary in rather complicated ways at distances from an antenna that are small compared with the wavelength λ of the radiation (33.3 cm at 900 MHz and 16.7 cm at 1800 MHz). Therefore detailed calculations are needed to obtain accurate values for the intensities and fields near to a phone and the approximate values given here are only intended to give indications of their size. The field values given above, when the antenna is a long way from the head or body, are from computed values for a particular antenna (Dimbylow and Mann, 1994; Mann *et al, in press*). The largest values of electric field E inside a model of a head whose surface is 1.4 cm from the antenna were also computed and are about 120 V/m for a 900 MHz antenna radiating 2 W and 70 V/m for a 1800 MHz antenna radiating 1 W. (These are obtained from their published figures of the specific absorption rates (SARs) inside the head; SAR is defined in paragraph 4.37). The value for the intensity was obtained by assuming the antenna to be a rod of length $l = \lambda/4$. The average value a distance r from the antenna is very roughly equal to $P/2\pi rl$ since nearly all the radiated power, P, has to pass through a cylinder of area $2\pi rl$. The intensities are the same for both 900 MHz and 1800 MHz GSM phones since P/l is the same for both.

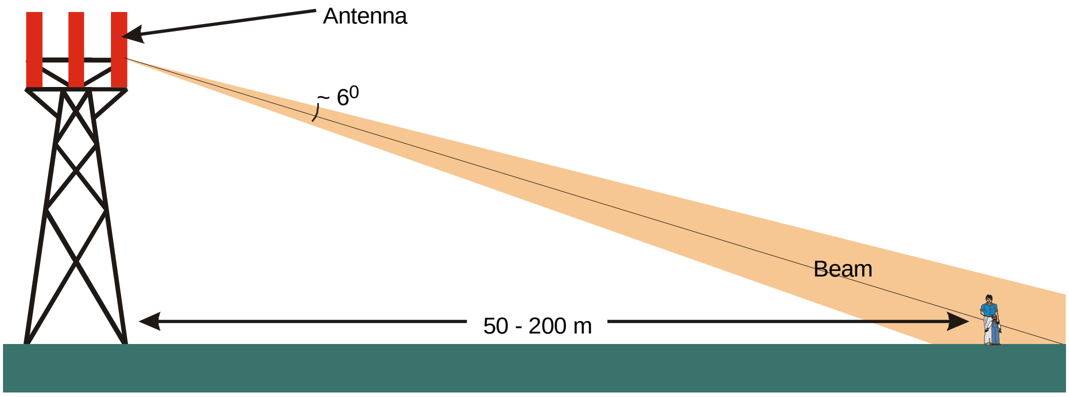

Figure 4.5 Main beam from an antenna mounted on a tower. The beam is in fact less well defined than that shown here and there is a series of weak side lobes either side of it

4.32 The licence sets the maximum EIRP at 1500 W per frequency channel corresponding to a maximum total radiated power of about 30 W per channel (= EIRP/gain). It also limits the number of channels per antenna to 16 (for 1800 MHz) and 10 (for 900 MHz). However, we have been told that in practice the number of channels is typically less than 4 for 1800 MHz and 2 to 4 at 900 MHz (FEI, 2000), which would correspond to maximum radiated powers of less than 120 W and 60–120 W, respectively. Similarly, the total radiated power emitted from an antenna is generally limited by the characteristics of the equipment to somewhat under 70 W (FEI, 2000), and a figure of 60 W will be assumed in this report. It needs to be stressed that the number of channels used, and hence the total radiated power, is limited by technical rather than legal requirements, which would in fact permit significantly larger powers to be radiated. As with a phone, and for largely the same reasons, the *average* power transmitted by a base station is normally less than the *maximum* power, although in this case it could rise to the maximum at times (rather than to one-eighth of the peak power in the case of a phone). By the inverse square law, the *maximum* intensity in the main beam at a point on the ground 50 m from a 10 m tower carrying an antenna transmitting 60 W into a 120° sector is about 100 mW/m^2 [*]. This corresponds to oscillating electric and magnetic fields of about 5 V/m and 0.02 µT, respectively, very roughly about 50 to 100 times smaller than those 2.2 cm from the antenna of a phone. The heating effects that these fields would produce will vary with the intensity and are about 5000 times smaller than the maximum value 2.2 cm from the antenna of a mobile phone.

4.33 The RF intensity on the ground is not zero outside the main beam, because of the power emitted into the side lobes. Its value will depend on the design of the antenna but it seems unlikely that it could ever be significantly more than that within the beam. So the values given above should be reasonable indications of the maximum intensity and fields that would be present on the ground around a base station. The intensity will, however, become appreciably larger as the antenna is approached, as it might be by maintenance workers.

---

[*] If the power P were transmitted equally into all directions, the intensity at a distance r would be $P/4\pi r^2$ (the power passes through a sphere of area $4\pi r^2$) which is about 2 mW/m^2 at a point on the ground 50 m from the bottom of a 10 m tower transmitting P = 60 W. For a 120° sector antenna with a gain of 50 the intensity at the centre of the beam rises to around 100 mW/m^2. However, even though the intensity *at a particular distance* is greatest at the centre of the beam, the intensity on the ground is somewhat larger at angles just away from the centre since the distance from the antenna is less (see Figure 4.5). So the region of greatest intensity lies between the points where the centre of the main beam hits the ground and the points where the nearest edge of the beam hits the ground (for this purpose we define the edge as occurring at the angle at which the intensity falls by half, 3 dB). In this report we refer to the part of the beam producing this region as the *beam of greatest intensity*.

4.34 In the last year or so NRPB has made spot checks on the average intensities around base stations. Eight of these stations were mounted on the roofs of schools; four were on tower blocks and five on other buildings. Measurements were made at various points within the buildings, at ground level or at other locations of public access (Mann *et al*, *in press*). The measured intensities were typically between 0.01 and 1 mW/m^2 and the maximum was never more than 10 mW/m^2. These values are then very much less than the calculated values in the beam given above, although the sample is small. It is also of note that the calculations and most of the measurements were for towers used by one operator only. The average intensities would be expected to be larger near to a tower used by more than one operator.

4.35 We note that these measurements by NRPB were spot checks made under contract at the request of a client such as a local authority. Neither NRPB nor any other independent agency has made any systematic experimental study in the UK of, for example, how the intensity changes with distance from a base station, although such studies have been reported in the USA. The NRPB report also includes the measurements made during these spot checks of the intensities due to radio and TV transmissions but again there have been no systematic studies which would have allowed us to make a useful comparison of the intensity of typical exposure levels received by individuals from mobile phone transmitters compared with those from other RF sources. Surveys of this sort have been conducted in the USA but they are several years old and have been made obsolete by the rapid development of wireless technologies. This is, indeed, a very complex problem given the great diversity of RF sources that are presently in operation.

4.36 Two further properties of the electromagnetic waves emitted by both mobile phones and base stations, that might be of significance in their interaction with biological tissue, are their frequency spectrum and coherence time. The emission from a mobile phone is essentially at one frequency and that from a base station is at several specific frequencies and, in both cases, the waves have the relatively long coherence time of around 4 μs (the coherence time is the average time between random phase changes, which in this case are the result of phase modulation, see paragraph 4.11). Both these properties are very different from those of, say, the radiation from the Sun which consists of a broad spectrum of frequencies and electromagnetic waves with coherence times which are shorter by a factor of around a hundred-thousand.

Field penetration into the body: dosimetry

4.37 Radiofrequency fields penetrate the body to an extent that decreases with increasing frequency. To understand the effects this might have on biological tissue, the magnitude of the fields needs to be determined within the various parts of the body that are exposed. This requires a knowledge of the electrical properties of the different types of tissue and, once this has been determined, it is possible to calculate E and B at every part of the body caused by a particular source of radiation such as a mobile phone. The rate at which the energy is absorbed by a particular mass of tissue m, is $m\sigma E^2/\rho$, where σ and ρ are, respectively, the conductivity and density of the tissue and E is the rms value of the electric field. The quantity $\sigma E^2/\rho$ is called the specific energy absorption rate or SAR and is measured in watts per kilogram (W/kg). It varies from point to point in the body both because the electric field changes with position and 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 at 900 MHz and the density of body tissue are 1 S/m and 0.001 kg/m^3, respectively, the typical value of electric field needed to produce an SAR of 1 W/kg is about 30 V/m. (The average value of conductivity is somewhat higher at 1800 MHz so lower electric fields, about 25 V/m, are needed.) The SAR produced by a particular value of electric field is somewhat larger in children than in adults because their tissue normally contains a larger number of ions and so has a higher conductivity (Gabriel, 2000). We understand that an internationally agreed standard testing procedure that will allow the SAR from mobile phones to be compared is being developed and will be finalised this year (2000).

4.38 It is important to stress that these are the electric fields *inside* the body. The fields outside the body that correspond to these internal fields are typically around three times larger; this was discussed in paragraph 4.28.

4.39 It is very well established that electromagnetic radiation can only be absorbed in quanta of energy $h\nu$, where h is Planck's constant. Now the energy needed to remove an electron from (ionise) an atom or molecule is a few electron volts (eV)[*] (an eV is the energy needed to move an electron of charge e from an earthed plate to one at a negative voltage of one volt). So if the quantum of energy is less than about 1 eV, it is essentially impossible for ionisation to occur[†]. The quantum of energy of RF radiation is in fact many thousand times less than 1 eV so RF radiation cannot ionise atoms or molecules and is described as non-ionising radiation (NIR). However, higher frequency radiation, such as far-ultraviolet radiation and X-rays, has energy quanta bigger than 1 eV and so can readily ionise atoms and molecules, and produce some damage to biological tissue even at very low intensities. This is referred to as ionising radiation. The intensity determines the number of quanta striking the body per second and, even though this is small at low intensities, each quantum still has a certain probability of ionising and so damaging biological molecules such as DNA. Non-ionising electromagnetic radiation, however, is believed to be harmless at very low intensities, although it can be damaging at high intensities. For example, light at modest intensities produces useful biological effects which allow us to see illuminated objects. However, if the intensity of the light becomes too large, the eye can be seriously damaged. Very high intensity RF radiation can also be damaging as is clear from the strong heating effects produced in a microwave oven. So we need to know at what intensity the radiation starts to produce damage; this might usually be expected to be higher than the lowest intensity at which biological effects can be detected. The current guidelines that are in force to protect people from harmful exposures are discussed in paragraphs 6.19–6.32.

---

[*] The ionisation energy has been quoted as a few electron volts, although the usual boundary between ionising and non-ionising radiation in biological material is taken as around 10 eV, reflecting the fact that the atoms that are present have ionisation energies that are greater than average.

[†] It is possible for two or more quanta to be absorbed simultaneously. However, the probability of this happening falls rapidly with the number of quanta and becomes minute if thousands of quanta are to be absorbed at the same time.