2 SOURCES, MEASUREMENTS AND EXPOSURES

This chapter begins by explaining the physical principles and terminologies relating to radiofrequency (RF) electromagnetic fields (EMFs) and their sources. It then describes particular sources and the field levels that arise around them, and finishes by briefly describing instrumentation and methods that can be used for assessing and defining exposure to EMFs. The chapter serves to present technical background material useful for the interpretation of material in the later chapters of this monograph. Readers should refer to text books in order to understand detailed aspects of electromagnetic physics and engineering. Technical standards and measurement codes of practice also provide useful information on the detailed aspects of exposure assessment from sources.

2.1 Physical characteristics of electromagnetic fields

2.1.1 Electromagnetic fields and radiation

The field concept is very general in physics and describes for each point in a region of space the specific state of a physical quantity. Although a field can be defined for almost any physical quantity, it is in common use only for those which are capable of exerting a force. The gravitational field, for example, describes the force exerted on a unit mass at each point in space. Accordingly, the electric field describes the force exerted on a unit electric charge, and the magnetic field is defined in terms of the force exerted on a moving unit charge.

As explained by WHO (2007), electric fields are produced by electric charges, irrespective of their state of motion, and are related to the voltages on charged objects. Magnetic fields are produced by moving charges and thus are proportional to electric currents in a system, irrespective of the voltage used. As long as charges and currents are static, i.e. they do not change with time, electricity and magnetism are distinct phenomena.

Time-varying charge distributions or currents imply that charges are being accelerated. Acceleration of charges results in a radiation component, in addition to the “quasi static fields” that arise from resting and moving charges. At low frequencies the radiating field of a source is negligible and radiation fields only become dominant over quasi static fields at distances that are large compared to the wavelength (see section 2.1.4).

The fundamental equations of electromagnetism, Maxwell’s equations, describe the coupling between the fields, and imply that a time-varying electric field generates a time-varying magnetic field and vice versa. The coupling of the electric and magnetic fields becomes stronger with increasing frequency and the fields are described as “interdependent”. Ultimately, and at distances that are large in relation to the wavelength, the fields combine together to form a propagating electromagnetic wave.

Radiation is the process through which energy travels, or propagates, through space or some other medium in the form of waves or particles. Electromagnetic (EM) radiation specifically refers to the wave-like mode of transport in which the energy is carried by electric (**E**) and magnetic (**H**) fields that vary in planes perpendicular to each other and to the direction of energy propagation. Just as electric and magnetic fields are vector quantities, with both magnitude and direction, the energy they carry has a magnitude and direction that is described by the pointing vector (**S**).

2.1.2 Quantities and units

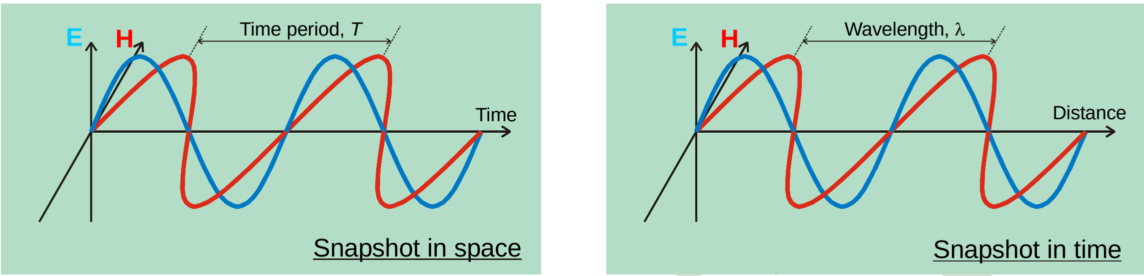
2.1.2.1 Frequency and wavelength

The variations of **E** and **H** with time depend only on the source of the waves, and most man-made sources of EM radiation produce waves with field strengths that vary approximately sinusoidally, as shown in Figure 2.1a. The number of cycles per second is known as the frequency, *f*, and is quantified in the unit hertz (Hz). The waves travel at the speed of light (3×10^8 m/s), *c*, in free space and in air, but more slowly in dielectric media, including body tissues. The wavelength, λ, as shown in Figure 2.1b, is the distance between successive peaks in a wave and is related to the frequency according to

$$\lambda = \frac{c}{f} \qquad (2.1)$$

A consequence of this relationship is that the wavelength of EMFs at a given frequency is shorter in biological tissues than in air.

It should be noted that the perfect sinusoidal case shown in Figure 2.1, where a wave has a sharply defined frequency, is somewhat ideal and that man-made waves usually contain an element of noise-like changes in frequency over time that result in the energy they carry being spread over a range of frequencies about the fundamental frequency. Waves from some sources may have purely random variations over time and no evident sinusoidal character. Some field waveforms, particularly with some high-powered industrial sources, can have a distorted shape while still remaining periodic. This corresponds to the presence of harmonic components at multiples of the fundamental frequency.



(a) (b)

Figure 2.1. A sinusoidally varying electromagnetic wave viewed in time at a point in space (a) and in space at a point in time (b).

The strength of the electric or magnetic field can be indicated by its temporal peak value (either positive or negative), although it is more usually denoted by the rms, or root mean square, value (the square root of the average of the square of the field strength over time). For a sinusoidally varying field, the rms value is equal to the peak value divided by $\sqrt{2}$. At a sufficient distance from the source where the wave can be described as a plane wave (see section 2.1.3), the electric and magnetic field directions are at right angles to each other and also to the direction in which the energy is propagating.

2.1.2.2 Electromagnetic spectrum

As mentioned above, electromagnetic waves are characterised by an electric field strength, *E*, expressed in the unit volt per meter (V/m), and a magnetic field strength, *H*, expressed in the unit ampere per meter (A/m), which typically oscillate sinusoidally between positive and negative values at a frequency, *f*.

Electromagnetic radiation interacts differently with matter according to its frequency and a variety of different terms, as shown in Figure 2.2, are used to refer to radiation with different physical properties. As frequency increases, so the energy of the individual photons (quanta, or packets of energy that make up the radiation) increases proportionally. Radio waves are referred to as non-ionising radiation because the photon energy is far too small to cause the removal of electrons from atoms (see Chapter 4).

The figure shows frequency increasing from left to right, with the prefixes kilo-, mega-, giga- and tera- before hertz denoting multipliers of 10^3, 10^6, 10^9 and 10^{12}, as in kHz, MHz, GHz and THz. EMFs in the RF range can be used readily for communication purposes as radio waves. The International Telecommunications Union (ITU) has developed a categorization scheme for radio waves according to their frequency decade and this is shown in Figure 2.2 (ITU, 2008). The nine RF bands defined by ITU are VLF, LF, MF, HF, VHF, UHF, SHF and EHF denote Very low, Low, Medium, High, Very High, Ultra High, Super High and Extremely High Frequencies respectively.

While there is no abrupt physical cut-off to the radio spectrum at low frequencies, it becomes progressively more difficult to produce antennas that can radiate energy efficiently, especially below a few tens of kHz, because of their small physical size in relation to the long wavelengths involved. Nevertheless, capacitive and inductive coupling, involving quasi-static electric and magnetic fields respectively, are still used for many applications. For the purpose of this monograph, a lower frequency of 100 kHz (wavelength of 3 km), i.e. mid-way through the LF band, will be considered.

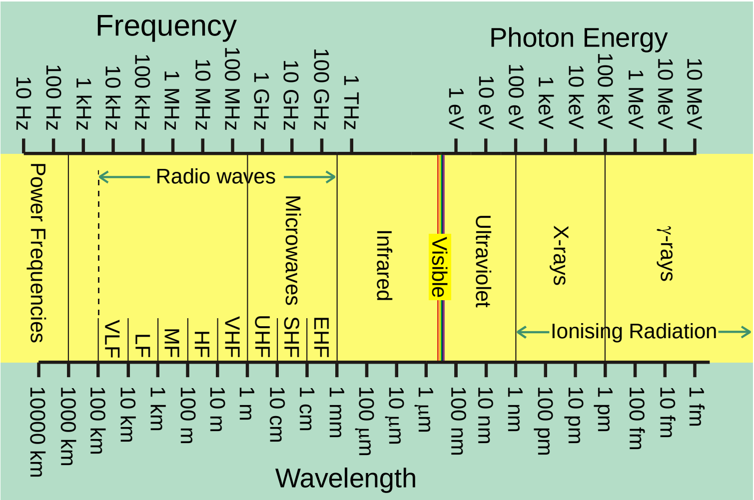


Figure 2.2. The electromagnetic spectrum.

Radio waves with frequencies in the range 300 MHz to 300 GHz can be referred to as microwaves, although this does not imply any sudden change in physical properties at 300 MHz. Similarly, the choice of a frequency of 2.45 GHz for heating of food in microwave ovens does not reflect any specific physical property of that particular frequency. Heating is a property of all radio waves because the energy they carry can be deposited in materials (see Chapter 4).

Above the frequencies used by radio waves are the infrared, visible ultraviolet, X-ray and gamma-ray portions of the spectrum. At infrared and up to around the ultraviolet region, it is conventional to refer to the radiation wavelength, rather than frequency. Photon energy is generally referred to in the X-ray and gamma-ray regions, and also to some extent in the UV range, because the particle-like properties of the electromagnetic radiation become more obvious in these spectral regions.

Below the RF portion of the spectrum lie EMFs that are mostly used for applications other than radio communication. The interdependence of the electric and magnetic field components also becomes less strong and they tend to be considered entirely separately at the 50/60 Hz power frequencies associated with distribution of electricity (WHO, 2007).

2.1.2.3 Polarisation

Electric and magnetic fields are vector quantities, i.e. they are characterized by an intensity (the field strength) and a direction. Direction and field strength are constant over time for static fields, while time-varying fields generally have varying field strength and direction over each period of oscillation.

With RF EMFs, it is conventional to refer to the behaviour of the electric field component in describing the polarisation. Linear polarisation is when the electric field remains parallel to a particular direction, and includes horizontal and vertical polarisations. Antennas having currents that oscillate parallel to an axis or which circulate about an axis produce fields with linear polarisation, as shown in Figure 2.1.

Circular polarisation is when the field vector rotates within a plane over each period of a wave, and can be either right-handed or left handed with respect to the direction of propagation. Circularly polarised waves are produced by sources having current distributions in more than one direction and where the current distributions are out of phase in the different directions. A typical example of a source producing circular polarisation is a helically wound antenna designed to radiate in its axial direction (normal mode).

The most general case of wave polarisation is known as elliptical polarisation and occurs when there is a dominant linear polarisation, in that the field is at a maximum at two opposite points during the period of its rotation and at a minimum (but not zero) at the two intermediate points.

2.1.2.4 Wave impedance

The ratio of the strength of the electric field component to that of the magnetic field component is constant in an electromagnetic wave and is known as the characteristic impedance of the medium, η, through which the wave propagates.

$$\eta = \frac{E}{H} \qquad (2.2)$$

The characteristic impedance of free space and air are equal to 377 Ω, where the unit ohm (Ω) has the same dimensions as electrical resistance.

2.1.2.5 Power density

The energy flowing per unit area per second at a point in an EMF is called the power density, *S* and is expressed in the unit watt per square meter (W/m^2). Beyond about one wavelength from a transmitter (see section 2.1.4 for more explanation), the positive (or negative) peaks in the electric and magnetic fields coincide in space and time, i.e. the fields are in phase. Under these conditions, the power density equals the rms electric field strength multiplied by the rms magnetic field strength, i.e.

$$S = EH \qquad (2.3)$$

Also, when the wave impedance, η, is equal to 377 Ω, the following two expressions can be used to simply evaluate power density from the measured electric and magnetic fields.

$$S = \frac{E^2}{377} \quad \text{and} \quad S = 377H^2 \qquad (2.4)$$

Power density decreases with increasing distance from the source because the waves spread out as they travel. In free space, power density beyond a certain distance from sources follows the inverse-square law such that *S* is proportional to $1/d^2$, where *d* is the distance from the source (see section 2.1.4.1).

2.1.2.6 Summary of quantities and units

A summary of quantities and units commonly used at radiofrequencies is provided below.

Table 2.1. Quantities and units commonly used at radiofrequencies

Quantity	Symbol	Unit	Symbol
Conductivity	σ	Siemens per meter	S/m
Permittivity	ε	Farad per meter	F/m
Current	*I*	Ampere	A
Current density	*J*	Ampere per square meter	A/m
Electric field strength	*E*	Volt per meter	V/m
Power density	*S*	Watt per square meter	W/m^2
Frequency	*f*	Hertz	Hz
Impedance	*Z*	Ohm	Ω
Magnetic field strength	*H*	Ampere per meter	A/m
Propagation constant	*k*	Per meter	/m
Specific absorption	SA	Joule per kilogram	J/kg
Specific absorption rate	SAR	Watt per kilogram	W/kg
Wavelength	λ	Meter	m

2.1.3 Waveforms

When considering how to categorise and quantify human exposure, it is important to account consistently for the characteristics of particular communication systems, especially when summing the exposure contributions from different signals together in the context of a chosen exposure metric. This involves considering whether the waveform is continuous or intermittent and whether the way information is carried affects important aspects of the signal (Foster & Repacholi, 2004). Aspects of signal characteristics relevant to developing exposure metrics are described below.

2.1.3.1 Modulation

The signals generated by various sources across the spectrum may be very different in character. While the underlying waveform from a source is usually sinusoidal, the signal may then, for example, be amplitude modulated (AM) or frequency-modulated (FM) for radio communication. The aim of modulation is to carry a message signal, such as a speech signal, on another signal that can be physically transmitted. The RF signal that carries the message information is called the *carrier* wave.

Older radio communication systems tend to use analogue modulation in which a carrier signal is produced with a suitable frequency to be transmitted and then some aspect of this signal is varied in relation to a lower frequency *baseband* signal that contains the information to be transmitted. With amplitude modulation (AM), the amplitude of the carrier signal is made proportional to the amplitude of the baseband signal, whereas in frequency modulation (FM) it is the frequency of the carrier signal that is made proportional. Phase modulation (PM) is very similar to frequency modulation in that changes in frequency are used to advance or retard the oscillations of the modulated signal with respect to a notional unmodulated carrier.

Modern digital radio communication systems can use more than one type of modulation in the same signal, generally a mixture of amplitude and phase modulations. To understand these systems it is helpful to produce a diagram showing how the amplitude and phase of the modulated signal vary over time. Figure 2.3 shows the evolution of a TETRA signal over a period of 14 ms (AGNIR, 2001). At a point in time, the distance from the origin of the chart denotes the amplitude of the signal in relation to the carrier (unity being equal to the carrier amplitude), while the angle with respect to the positive *x*-axis denotes the phase of the signal in relation to the carrier. Alternatively, the *xy* co-ordinate read from the diagram at a point in time describes the in phase (I) and quadrature (Q) components of the signal. A purely amplitude modulated signal would remain along the *x*-axis of the figure, whereas a purely phase modulated signal would move around a circle.

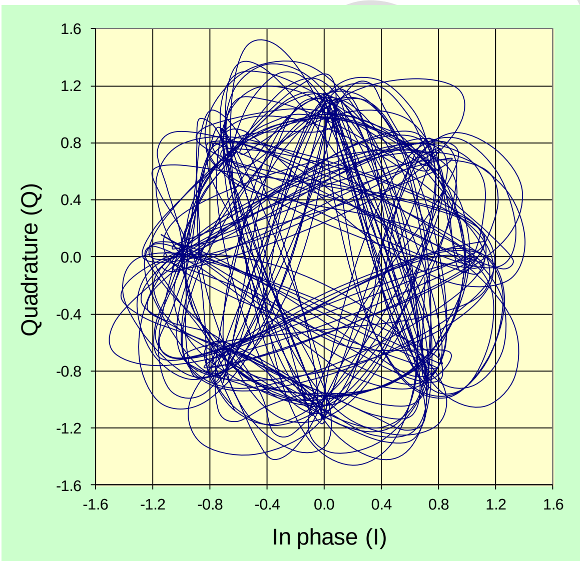


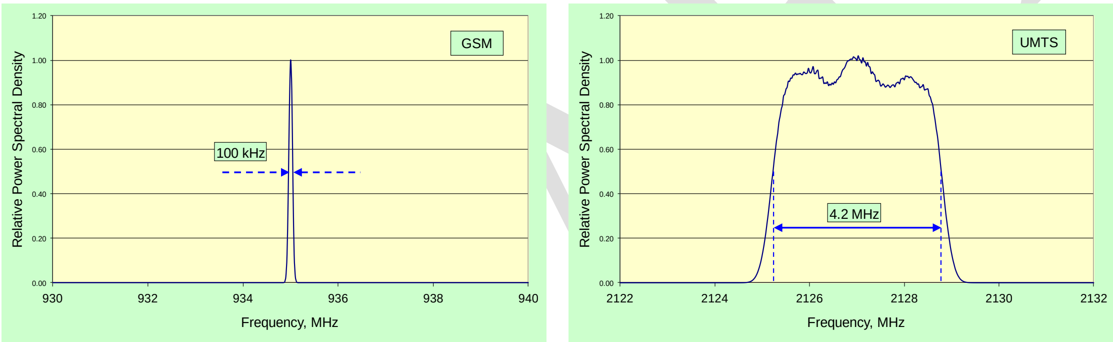
Figure 2.3. Amplitude and phase evolution of a digitally modulated radio signal over time (AGNIR, 2001).

The changes in the amplitude and phase of digital radio signals are known as symbols and they occur over fixed intervals. For example, GSM signals for mobile phones encode 270,833 symbols per second so each symbol is of around 3.7 µs duration. In the most basic mode of GSM systems, known as minimum shift keying (MSK), the symbol can either be a phase advance of 90° or a phase retard of 90°, according to whether the data bit to be encoded is a binary 1 or 0. Some systems can encode more than one data bit per symbol. For example, the TETRA system illustrated in Figure 2.3 involves symbols that are changes of either ±45° or ±135° in phase, i.e. there are four possibilities. This is evident from the trajectory of the data and in that eight nodes can be seen around the unit circle at 45° spacing. The four symbols are mapped onto the binary data elements: 00, 01, 10 and 11, i.e. two binary bits are encoded per symbol.

2.1.3.2 Bandwidth

A perfect sine-wave, if considered in the frequency domain, would have all of its energy concentrated at a single frequency. However, all oscillators have small random variations in the frequency they produce and these result in the signal energy being spread over a range of frequencies in practice. Typically, the distribution of energy as a function of frequency is Gaussian in shape and a common figure of merit is the half-power (or 3 dB) bandwidth. This is the difference between the two frequencies at which the signal power spectral density (in watts per Hz) is equal to half of that at the maximum. For a typical unmodulated signal at telecommunications frequencies of around 1 GHz, the bandwidth may only be a few tens of Hz.

Modulation increases the bandwidth of the carrier signal appreciably because of the distortions to the pure sinusoidal shape that are deliberately introduced. Some modulation schemes are relatively narrow-band in character, for example TETRA signals at 400 MHz have half-power bandwidth of around 10 kHz. GSM signals at 900/1800 MHz have a wider bandwidth of around 100 kHz and UMTS signals for 3G mobile phones have bandwidths of around 4 MHz, as shown in Figure 2.4. For all of these systems, the signal bandwidth is small in relation to the carrier frequency. There are, however, some systems for which the signal energy may be spread over a very wide bandwidth. The International Telecommunications Union defines ultra-wide band (UWB) systems as those where the signal's 10 dB bandwidth exceeds the lesser of 500 MHz or 20% of the centre frequency in publication ITU-R (ITU, 2006).



(a) (b)

Figure 2.4. Examples of measured spectra for typical GSM (a) and UMTS (b) modulated signals.

2.1.3.3 Orthogonal Frequency Division Multiplexing (OFDM)

Systems that use orthogonal frequency division multiplexing (OFDM) have multiple carriers closely spaced in frequency, each of which carries digitally modulated data. The frequency separation of the individual carriers is made equal to the rate at which symbols are encoded onto each carrier. Under this special condition, it becomes possible for the receiver to recover the data even though the spectra of the individual modulated carriers overlap. The system makes very efficient use of the radio spectrum and the signals are recognisable when measured with a spectrum analyser because of their flat-topped rather than Gaussian shape. An example of such a system is Digital Video Broadcasting for television (DVB-T) with 1705 carriers separated by 4.464 kHz, i.e. a total signal bandwidth of 7.6 MHz occupies the 8 MHz wide channels assigned in the spectrum.

The number of bits transmitted per symbol by OFDM systems is proportional to the number of carriers, which is useful property for systems where the bandwidth demands of individual users can vary. This is now the case for users of mobile devices connected to cellular networks, who can be watching video carrying out voice calls, or engaged in a variety of other types of data transfer. Hence, the latest 4G mobile phone systems use OFDM and vary the number of carriers assigned to each user dynamically according to their needs and to manage use of the available spectrum.

2.1.3.4 Pulsing (pulse modulation)

RF signals are often transmitted in a series of short bursts or pulses, for example, in radar applications. Radar pulses last for a time that is very short compared with the time between pulses. Typically, the pulse duration could be one microsecond (one-millionth of a second), while the time interval between pulses could be one millisecond (one-thousandth of a second). The detected signal arises from reflections from objects where the distance of the object is determined by the time between a transmitted pulse and its reflection. The long interval between pulses is needed to ensure that an echo from the most distant object arrives before the next transmitted pulse is sent. Thus, with a pulse modulated signal the time-averaged power is lower than the peak power (power during transmission) by a quantity known as the duty factor. Duty factor is the ratio of the time-averaged power, P_{avg}, to the peak power, P_{peak}.

$$\text{Duty Factor} = \frac{P_{peak}}{P_{avg}} \tag{2.5}$$

Note, the use of Time-Division Multiple Access (TDMA) in communications systems can introduce pulse modulation for reasons that are explained in the next section.

2.1.3.5 Multiple access methods

The radio spectrum is a limited resource that has to be shared between many users. The simplest form of sharing occurs in radio systems where individual users are assigned different carrier frequencies for their transmissions and the spectra of the individual signals do not overlap. This is known as Frequency Division Multiple Access (FDMA) and is the basis on which analogue broadcast radio signals for music and television are separated according to their frequency channel. FDMA was the only form of resource sharing used by the first generation of (analogue) mobile phones. Note also that mobile phone systems generally use separate frequencies for the uplink (mobile to base station) and downlink (base station to mobile), which is known as Frequency Division Duplex (FDD).

Some modern digital systems involve radio transmitters that take it in turns to transmit while using the same frequency channel, which means that the signals from any given transmitter are pulse modulated. This form of resource sharing is known as Time Division Multiple Access (TDMA). It should be noted that, with cellular radio networks (see Section 2.2.2.2), it is the mobile terminals (handsets) that take it in turns to transmit to the base stations and thus transmit intermittently, whereas the base stations serve each user in turn and can therefore transmit continuously.

Signals from many second generation mobile phone systems, including GSM and TETRA, involve the use of TDMA in addition to FDMA. For GSM, a 0.58 ms pulse is transmitted every 4.6 ms, resulting in pulse modulation at a frequency of 217 Hz. A lesser degree of pulse modulation also occurs at 8.34 Hz because every 26^{th} burst is missed out. For TETRA handsets and mobile terminals, the main pulse frequency is 17.64 Hz and bursts are of 14.17 ms duration. Note, every 18^{th} burst is missed out with TETRA mobile and portable terminals in trunk mode operation (see Section 2.2.4), leading to the presence of a weaker pulse modulation component at 0.98 Hz. Further information about the pulsing characteristics of different systems, including DECT cordless phones and Wi-Fi, is given with information about those particular sources later in this chapter.

Third generation, and also some second generation, mobile phones use code division multiple access (CDMA), which allows several users to use the same frequency channel simultaneously by ‘labelling’ each of their transmissions with a specific coding scheme. Communications are carried out between handsets and base stations using frequency division duplex (FDD) mode, although a time division duplex (TDD) mode is also provided for by the standard. Each transmission is continuous and so there is no pulsing, although the adaptive power control updates that occur at a rate of 1500 Hz will cause this component to ‘colour’ the otherwise broad spectrum of the power modulation. With TDD mode, transmissions would be produced in bursts at the rate of 100 Hz and so pulsing would occur at this frequency, in addition to the frequency of the adaptive power control.

Fourth generation mobile phones use OFDM and assign appropriate numbers of sub-carriers to each user dynamically in order to balance usage and share the radio resource.

2.1.4 Field regions around sources

2.1.4.1 Far-field conditions and the inverse square law

The far-field region refers to locations at greater distances from a source than the extent of the two near-field regions described below. In this region, the angular distributions of the electric and magnetic fields about the source are essentially independent of distance and the fields have a predominantly plane wave character, i.e. there are uniform distributions of electric and magnetic fields in planes perpendicular to the direction of propagation. Also, the electric and magnetic fields are perpendicular to each other, with their magnitudes related such that $E/H = 377\ \Omega$. Figure 2.5 shows planes at various distances from a source in which the phase of the EMFs is constant. The figure illustrates how far-field conditions become established with increasing distance and how they can be disrupted locally by radiating near-fields from reflecting and scattering objects.

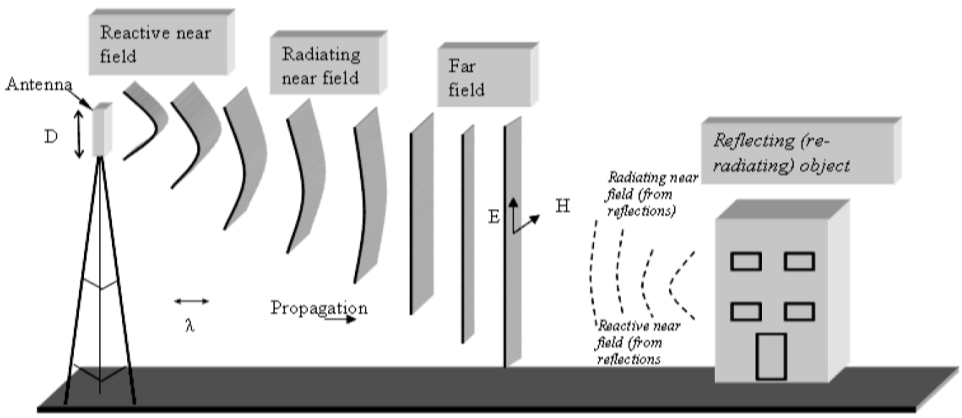


Figure 2.5. Near- and far-field regions around a radiating antenna (ICNIRP, 2009).

While some sources are designed to radiate preferentially in certain angular directions, the radiated power generally spreads out around all sources. If one considers a hypothetical point source that radiates power equally in all directions, it is evident that, at any given distance, d, the power is passing through a spherical surface of area $4\pi d^2$. Thus, the power density (the power flowing through the surface per unit area) at a given distance is equal to the radiated power divided by $4\pi d^2$. This is the well-known inverse square law.

The inverse square law is modified for many radio communications applications to include a dimensionless parameter known as antenna gain, G, which quantifies the extent to which an antenna directs the power it radiates in a certain desired direction: that of its main beam. In order to do this, the antenna has to redirect power from undesired directions and so produce a narrower beam. For an antenna of gain, G, and radiating a power, P, in watts, the power density, S, at a given distance can be calculated with the equation below and has the unit watt per square metre.

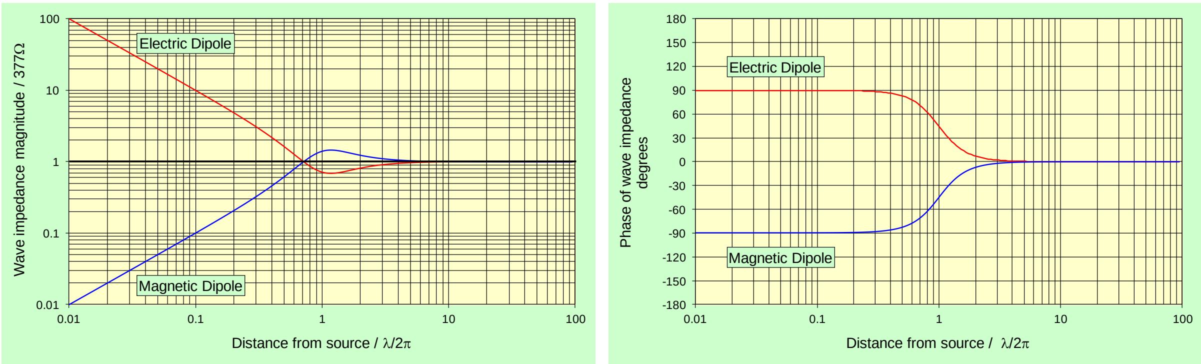
$$S = \frac{PG}{4\pi d^2} \qquad (2.6)$$

For real antennas having finite size the above equation is only valid at distances in the far-field region. At lesser distances, the power density and the associated EMFs have a complicated variation with distance and angle. The near-field regions in which this occurs are described below.

2.1.4.2 Reactive near-field

In general, the fields near to RF sources can be divided into two components: radiating and reactive ones. The radiating components are associated with that part of the field which propagates energy away from the source, while the reactive components can be thought of as storing energy in the region around the source. The stored energy oscillates back and forth with respect to the source over the sinusoidal period of the wave such that none escapes in a purely reactive field. In a field that has both reactive and radiating elements, there is a net loss of energy (radiation) over the wave period.

Reactive field components dominate close to sources in the *reactive near-field region*, whereas radiating components dominate at greater distances. A distance of around one sixth of a wavelength, or $\lambda/2\pi$, from sources is often taken to define the extent of the reactive near-field region, although there is no sudden change in field characteristics. It is also possible to define the reactive near-field as extending to $\lambda/10$ from sources and the far-field as extending beyond 3λ such that the region between these distances is regarded as a transition field. This is apparent from Figure 2.6, which shows how wave impedance varies with distance from small (infinitesimal) electric and magnetic dipole sources. The equations describing the fields from infinitesimal dipole sources can be found in text books, e.g. Balanis (2005).



(a) (b)

Figure 2.6. Variation of wave impedance magnitude (a) and phase (b) with distance from infinitesimal electric and magnetic dipole sources showing the transition from reactive to radiating conditions around a distance of $\lambda/2\pi$ from the sources.

Within the reactive near-field, the spatial distributions of the electric and magnetic fields are effectively independent of each other. Generally, the electric and magnetic fields are not at right angles to each other and they do not reach their largest values at the same points in space. The wave impedance is greater than 377 Ω in the capacitive near-fields produced by electric dipole-like sources and less than 377 Ω in the inductive near-fields produced by magnetic dipole-like sources (see Figure 2.6).

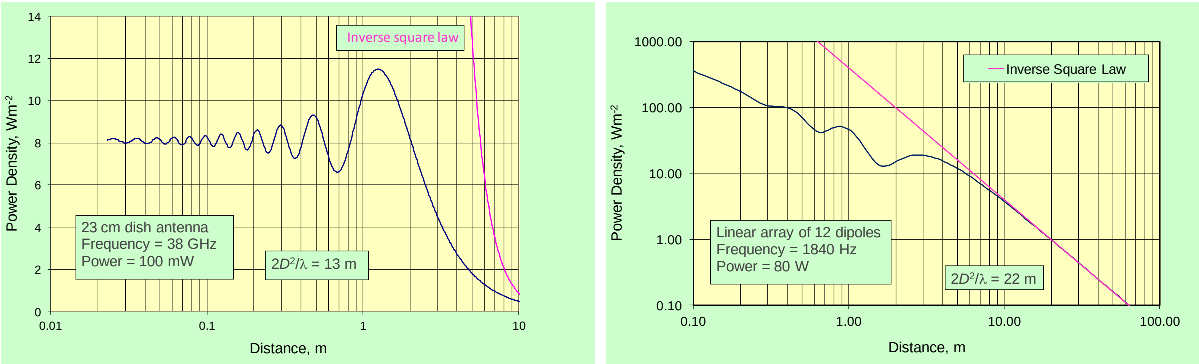
At telecommunications frequencies of around 900 MHz, the reactive near-field extends to about 5 cm, thus the fields to which a person is exposed when they hold a mobile phone to their head are predominantly reactive in nature. Conversely, exposure to the fields from base station transmitters in the environment and with radio devices held in front of the body is generally dominated by radiating components of the field. With high power industrial sources operating at frequencies up to a few MHz, the operators are exposed to predominantly reactive fields.

Whilst the reactive field components do not contribute to the radiation of energy, the energy they store can be absorbed in the body and indeed they provide a major contribution to the exposure of people in the near-field region. The measurement of the reactive components of the field can be particularly difficult since the introduction of a probe can substantially alter the field.

2.1.4.3 Radiating near-field

Sources that are large in relation to the wavelength of the RF fields they produce have a radiating near-field region that extends further than the reactive near field region, and it is only beyond this region that the far field region begins. A distance of around $2D^2/\lambda$ (where D is the largest dimension of the radiating part of the source or antenna) is conventionally taken to define the extent of the *radiating near field region*. Beyond this distance, any phase shifts affecting radiation from different parts of a source and therefore travelling different distances to an observation point will be less than $\lambda/16$ and the source will appear as a single Fresnel zone.

Distances between $\lambda/2\pi$ (the reactive near-field boundary) and $2D^2/\lambda$ form a transition region in which radiating fields are dominant. The wave impedance is equal to 377 Ω, and the electric and magnetic field components are orthogonal to each other. However, the angular distribution of the fields still changes with distance and there is an oscillatory dependence of the fields with increasing distance in any particular direction, as shown in Figure 2.7. The power density in the radiating near field region of antennas does not exceed $4P/A_e$, where P is the total radiated power and A_e is the effective area of the aperture (radiating part of the antenna). A_e can be calculated from $A_e = G\lambda^2/4\pi$.



(a) (b)

Figure 2.7. Example calculations showing the predicted variation of power density with distance in the radiating near field region of simple antenna models: (a) microwave dish antenna, and (b) omni-directional base station antenna.

Antennas with strongly directional characteristics, i.e. high gains, have radiating near-field regions extending to large distances, far in excess of any reactive field regions. For telecommunications antennas used with mobile phone base stations and having gains up to around 20 dB, the radiating near-field region may extend for a few metres, whereas for the very high gain (up to around 60 dB) dish antennas used for satellite communications it may extend for a kilometre or more. For low gain antennas, where D is of a similar size or smaller than the wavelength, the calculation indicates the radiating near-field does not extend beyond the boundary of the reactive near-field. Moreover, in practice it does not exist because such small antennas present a single Fresnel zone.

2.1.5 Signal fading and multipath propagation

Fading is a fundamental characteristic of RF fields in the environment, particularly at telecommunications frequencies. In general, radio waves are reflected from buildings and other structures, leading to multiple paths for radio power to follow from the transmitter to the receiver. The contributions arriving by these different paths travel different distances and so arrive at slightly different times. Also, the path lengths differ by amounts that are larger than the wavelength (typically ~10 cm at telecommunications frequencies), meaning that the signal contributions can sum together to reinforce or diminish at a given position. The consequence of multipath propagation is to create large variations in field strength in the environment over distances of the order of the wavelength, and also over short time intervals (fractions of a second). Various statistical models of fading have been developed and these may be found in telecommunications engineering text books.

The presence of fading due to multipath propagation means the exposure of a person is generally a dynamic quantity, even if that person is not moving, and that the statistical characteristics of the fading in space and time have to be taken into account in how exposure is assessed. This usually involves averaging exposure over time and space in some appropriate way so that a repeatable measurement is achieved.

The influence of fading is negligible in situations where there is a single dominant propagation path for radiation from a source to an exposed person. This occurs in environments that preclude reflections, e.g. inside as an anechoic chamber with absorbing walls, and in environments where any reflected components have travelled much longer distances than a directly incident component and so have much reduced field strengths in comparison with the direct component. Most source-focussed exposure assessments only consider the directly incident radiation components, but it is also important to consider how the environment in which a source is used affects exposures.

2.2 Sources of exposure

This section describes the characteristics of the EMFs from natural and man-made sources, and summarises available information about exposure levels for the most widespread sources and those producing the highest exposures. As explained earlier, the emphasis is on providing information of use for the later chapters in this monograph; hence, there is an emphasis on sources where exposures have been studied from a health perspective. Natural sources are considered first and then man-made sources are considered under several broad categories. The section draws upon, extends and updates material presented earlier reviews by ICNIRP (2009), AGNIR (2012) and IARC (2013).

RF EMFs from natural and man-made sources differ in their spectral and time-domain characteristics and this complicates comparisons of their relative strengths. The fields produced by natural sources have a much broader frequency spectrum than those produced by man-made sources and it is necessary to define a bandwidth of interest in order to draw comparisons. In a typical communications bandwidth of 1 MHz, man-made fields will generally appear orders of magnitude stronger than natural ones, whereas if the entire 300 GHz bandwidth of interest to this monograph is chosen, natural fields may sometimes appear stronger than man-made ones.

RF EMFs within the 100 kHz to 300 GHz spectrum considered in this document arise from a variety of man-made sources. The strongest fields to which people are exposed arise from the intentional use of the physical properties of fields, such as induction heating (including the industrial heating of materials and some cooking hobs), remote detection of objects and devices (anti-theft devices, radar, radiofrequency identification (RFID)), communication (radio, television, mobile phones, wireless networks), diagnostics and therapy (MRI, hyperthermia), microwave ovens and many more. There are also unintentionally generated fields, such as those from the electronic ballasts used with modern fluorescent lighting, electronic circuits, processors and motors.

When considering sources, it is helpful to clearly delineate the concepts of emissions, exposures and dose:

Emissions from an RF source are characterized by the radiated power, including its spectral and time-domain distributions. Other factors are the polarization and the angular distribution (pattern) of the radiation. For sources that are large relative to their distance from a location where a person is exposed, it also becomes necessary to consider the spatial distribution of the emitted radiation over the entire structure of the source to fully describe it as an emitter.

Exposure describes the EMFs from the source at a location where a person may be present in terms of the strength and direction of the electric and magnetic fields. If these vary over the volume occupied by a person (non-uniform exposure), possibly because the source is close to them, or has strongly directional characteristics, it becomes necessary to quantify the RF EMFs over the space occupied by the person. The exposure depends not only on the source emissions and the geometrical relationship to the source (distance, angular direction), but also on the effect of the environment on the radiated fields. This can involve processes such as reflection, shielding, and diffraction, all of which can modify the fields substantially.

Dose is concerned with quantities or effects inside the body tissues that are induced by the exposure fields. These include the electric or magnetic field strength in the body tissues and the specific energy absorption rate (SAR). Note, SAR may be viewed as a dose rate quantity since it denotes the rate at which energy is absorbed per unit mass. However, with SAR as a surrogate for temperature rise, the cumulative energy deposited over short time-periods is sometimes important, as well as the rate at which that energy is deposited over periods comparable to thermoregulatory time constants (see Chapter 3). Because body tissues are conductive, the strength of the electric fields within the body tissues is generally much smaller than that of the exposure fields outside the body.

In most situations, the concept of emissions leading to exposure and then dose is helpful, but there are situations in which the presence of an exposed individual and the dose received affect the emissions from a source. This means that the intermediate concept of exposure cannot be isolated meaningfully, and dose has to be assessed directly from the source emissions either through computational modelling or via measurement of fields inside the body tissues. When the way in which a source radiates is strongly affected by the presence of an exposed person, the source and the exposed person are described as “mutually coupled”; a classic example of this is when a mobile phone is used next to the body (see Chapter 3).

Typical emission characteristics of sources will be summarized here, along with exposure and dose information where they are available. However, it is important to recognize that fields typically vary greatly in the vicinity of sources and spot measurements reported in the literature may not be typical values to which people are normally exposed. This is because assessments are often designed to identify the maximum exposures that can be reasonably foreseen, e.g. for workers near sources, and to show that these do not exceed applicable exposure limits.

2.2.1 Natural sources

The natural electromagnetic environment originates from sources in space (extraterrestrial sources) and sources on the Earth (terrestrial sources). These include electrical discharges in the Earth's atmosphere, and radiation from the sun and space, as shown in Figure 2.8. Compared to man-made fields in most situations, natural fields are extremely small at RF. Characteristic of natural RF fields is a very broadband spectrum where sporadic high peak transients arise over a noise-like continuous background. Below about 30 MHz, natural fields arise mainly from lightning discharges during thunderstorms, the high-peak transients, while above this frequency broadband continuous radiation dominates.

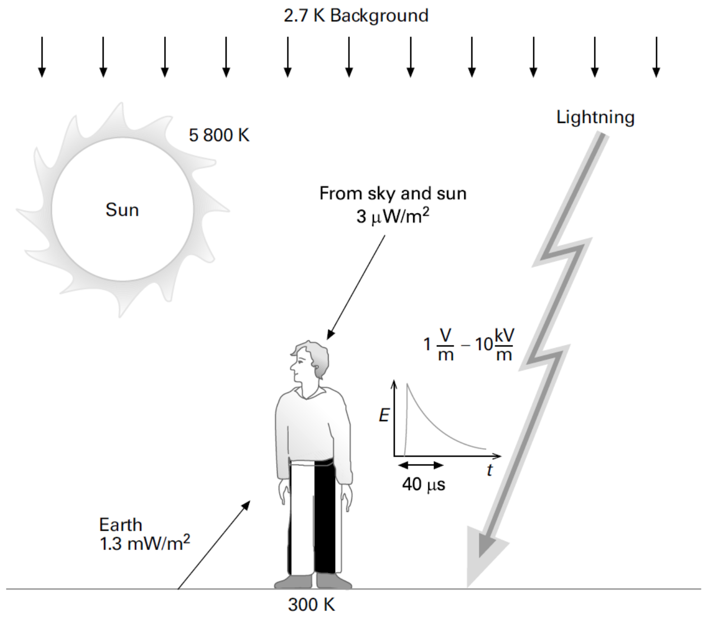


Figure 2.8. Terrestrial and extraterrestrial sources of RF radiation (ICNIRP, 2009).

Many natural sources emit RF and optical radiation according to Planck's law of "black body" radiation:

$$S(f,T) = \frac{2hf^3}{c^2}\frac{1}{e^{\frac{hf}{kT}}-1} \qquad (2.7)$$

where $S(f,T)$ is the power radiated per unit area of emitting surface per unit solid angle per unit frequency by a black body at absolute temperature T; h is the Planck constant, equal to 6.626×10^{-34}; c is the speed of light in a vacuum, equal to 2.998×10^{-8} m/s; k is the Boltzmann constant, equal to 1.381×10^{-23} J/K; f is the frequency of the electromagnetic radiation in hertz (Hz); and T is the temperature of the body in Kelvin (K) (Rybicki & Lightman, 2004).

Also, the total power emitted per unit surface area of a black body radiator can be evaluated by integrating Planck's equation over all angles in a half-space (2π steradians) and over all frequencies. This yields the Stefan-Boltzmann law, which describes how the power emitted by a black body radiator rises according to the fourth power of absolute temperature (Rybicki & Lightman, 2004):

$$S(T) = \frac{2\pi^5 k^4}{15c^2 h^3} T^4 \qquad (2.8)$$

These equations can be used to calculate the power density of the radiation from various types of natural sources, although it should be noted that, unlike man-made sources, such sources have no overall polarisation to the radiation they emit.

2.2.1.1 Extraterrestrial sources

Extraterrestrial sources include electrical discharges in the Earth's atmosphere, and solar and cosmic radiation. Heat remaining from the "big bang" at the formation of the universe is evident as the cosmic microwave background (CMB), with presents as black body radiation from all directions towards the Earth. The observed peak in the CMB spectrum presented per unit hertz is at a frequency of 160.2 GHz, which implies through Plank's equation a temperature of 2.725 K (Fixsen, 2009). Figure 2.9 shows the results of evaluating Plank's equation over the 30 kHz to 300 GHz frequency range. The total power density in this frequency range represents 80% of the total power density across all frequencies. Applying this factor to the results from the Stefan-Boltzman equation at 2.725K gives the power density incident on at the Earth's surface as 2.5 μW/m^2.

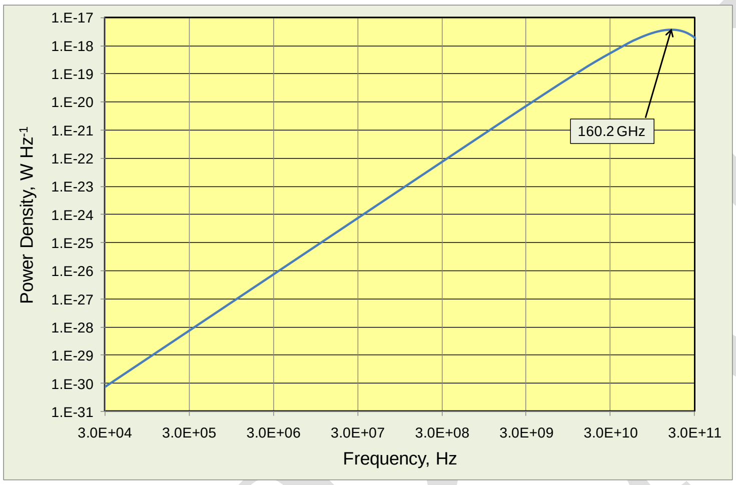


Figure 2.9. Power density spectrum of the cosmic microwave background over the 30 kHz to 300 GHz frequency range (IARC, 2013).

The sun is also a black body radiator and its spectrum shows a peak at 3.4 × 10^{-14} Hz, a wavelength of 880 nm, and commensurate with a surface temperature of 5778 K (NASA, 2013). Thus, based on Plank's equation, most of the sun's radiation is in the infrared region of the spectrum and only a small proportion is in the frequency range 30 kHz to 300 GHz. This fraction represents around 5 μW/m^2 of the total power density of 1366 W/m^2 incident on the Earth. This value is similar to that from the CMB, which contributes power from all directions, but the RF power from the sun is predominantly incident from the direction of the sun, and hence much reduced at night.

The atmosphere of the Earth has a marked effect on RF EMFs arriving from space. The ionosphere contains layers of charged particles between around 60 km and 600 km above the Earth's surface and has the property of reflecting RF EMFs at frequencies up to around 30 MHz away from the earth. Above a few tens of GHz, atmospheric water vapour and oxygen have a frequency-dependent attenuating effect on RF EMFs due to absorption. Oxygen absorbs strongly around 60 GHz and water vapour has a generally increasing attenuating effect with frequency, with absorption peaks around 22 and 183 GHz. These effects mean that the RF power density incident at the Earth's surface from sun and the CMB will be somewhat less than the 5 μW/m^2 values given for each above. ICNIRP (2009) quotes the total power density arising from the sky and sun as 3 μW/m^2 at the Earth's surface.

2.2.1.1 Terrestrial sources

The Earth itself is a black body radiator, with a typical surface temperature of around 290 K. As such, similar calculations to those above show that the majority of its emissions are in the infrared part of the spectrum but 0.0006% of the emitted power is in the RF region, and this amounts to 2.4 mW/m^2 from the Earth's surface. This is around a thousand times larger than the RF power density arising from the sky and sun.

People also produce black body radiation from their surfaces (skin). Assuming a surface temperature of 37 °C, i.e. 310 K, leads to a value of 2.5 mW/m^2 in the RF range. Then, with a typical skin area for an adult of 1.8 m^2 the total radiated power from a person is around 4.5 mW in the RF spectrum.

As mentioned above, the ionosphere effectively shields the Earth from extraterrestrially arising RF EMFs at frequencies below 30 MHz. However, lightning is an effective terrestrial source of RF EMFs below 30 MHz. The fields are generated impulsively as a result of the time-varying voltages and currents associated with lightning, and the waveguide formed between the Earth's surface and the ionosphere enables the RF EMFs generated to propagate large distances around the Earth.

On average there are around 40 strokes occurring every second on Earth, or 10 strokes per km^2 per year over land (NOAA, 2014). The EMFs from lightning strokes are impulsive in nature and vary depending on the nature of each stroke, and also according to the distance at which they are measured. Cooray (2003) described various mathematical models for return strokes, which are the strongest sources of RF EMFs associated with lightning processes. Peak electric field strengths of up to 10 kV/m[1] are possible within 1 km of strokes. At distances greater than 100 km, the field strength rises rapidly to a few V/m, with peak dE/dt of about 20 V/m per microsecond, and then reduces over a few tens of microseconds. Willett et al. (1990) measured the electric field strength during return strokes as a function of time and conducted Fourier analysis to determine the average spectrum between 200 kHz and 30 MHz. The energy spectral density reduced according to $1/f^{2}$ at frequencies up to about 10 MHz and more rapidly thereafter.

2.2.2 Environmental radio transmitters

There are many different types of radio transmitters present in the environment. The systems that have received most attention in health-related studies are described below, and these include those used for broadcast radio and television as well as the base stations that serve mobile phone networks. There are many other types of transmitters, for example the professional radio systems used by commercial organisations, emergency services and the military. There are also radio systems used by the public, including amateur (ham) radio operators and the users of citizens band radio.

Radio transmitters develop signals with the required technical characteristics and these are directed through cables to antennas that launch the radio waves. Field strengths generally reduce with distance, but from the perspective of potential exposure levels, there are a number of other factors to consider. Antennas with higher radiated powers generally produce stronger fields, but these may be in regions that are not accessible, depending on the location of the antenna and the angular pattern of radiation it produces. Also, the fields in the environment may be strongly perturbed, e.g. due to shadowing and reflections.

Omni-directional antennas are designed to provide an even distribution of field strength at ground level in all directions about them, while sector antennas are designed to establish an even distribution of field strength within a horizontal arc about them, for example 120 degrees. There are also highly directional antennas that are designed to transmit narrow beams from point to point. Most antennas (unless the intent is to communicate with satellites or aircraft) are designed to avoid directing radiation above the horizontal direction, since this power will be lost to the sky. They also tend to minimise the radiation directly downwards since any receivers below the antenna will be at very short distances and need minimal power directing towards them in order to enable reception.

2.2.2.1 Radio and television broadcasting

The frequency bands used for broadcasting of radio and television signals are broadly similar across many countries and are shown in Table 2.2.

Analogue broadcast radio has been available for many years and uses amplitude modulation (AM) in the long, medium and short-wave bands. More recent systems use frequency modulation (FM) in Band II and have become more popular for listening, especially to music, because of improved sound quality. The short-wave band continues to be important for international radio broadcasting because signals in this frequency band can be reflected from the ionosphere to travel around the world and reach countries 1000s of km away.

Table 2.2. Frequency bands used for broadcasting of television and radio signals

Designation	Frequency range	Usage
Long wave	145.5 – 283.5 kHz	AM radio
Medium wave	526.5 – 1606.5 kHz	AM radio
Short wave	3.9 – 26.1 MHz	International radio
VHF (Band II)	87.5 – 108 MHz	FM radio
VHF (Band III)	174 – 223 MHz	DAB and analogue/digital TV
UHF (Bands IV and V)	470 – 854 MHz	Analogue and digital TV

Band III was the original band for TV broadcasting and continues to be used for this purpose in some countries, while others have transferred their TV services to bands IV and V. Band III is also used for digital audio broadcasting (DAB); exclusively so in countries that have transferred all of their TV services to bands IV and V. Analogue and digital television transmissions share Bands III, IV and V, at present but many countries are in the process of transferring entirely to digital broadcasting.

AGNIR (2012) described the broadcast transmitter sites in the United Kingdom in terms of the numbers operating at a given power level in each frequency band (Table 2.3). There may be more than one transmitter of the quoted power at each site; for example, there would be up to five analogue television transmitters at each site; one for each TV station. At the time the data were collected, the digital TV network was not yet complete and was operating in parallel with the analogue one. However, shut-down of the analogue TV network was already in progress. These data may serve as a typical example of the range and distribution of transmitter powers used in a typical developed country.

The convention for reporting transmitter radiated power in the broadcast industry in the VHF and UHF bands is to use the quantity Effective Radiated Power (ERP). This contrasts with the quantity Equivalent Isotropically Radiated Power (EIRP), which tends to be used in other RF contexts. ERP is defined as the power, P_{ERP}, that would have to be radiated from a half-wavelength dipole antenna to produce the same field strength in the direction of the beam as is produced by the actual TV/radio antenna, whereas EIRP is the power, P_{EIRP}, that would have to be fed into an isotropic antenna to produce the same outcome. Thus EIRP is equal to ERP multiplied by a factor of 1.64, the gain of a dipole antenna (G_d). The power density at a given distance, $S(d)$, is given by the following expression in which G_i is the gain of the broadcast antenna with respect to an isotropic radiator:

$$S(d) = \frac{P_{rad} G_i}{4\pi d^2} = \frac{P_{EIRP}}{4\pi d^2} = \frac{P_{ERP} G_d}{4\pi d^2} \qquad (2.9)$$

The actual radiated power is typically around an order of magnitude lower than the ERP for typical transmitters in the VHF/UHF bands.

Table 2.3. Power levels and types of broadcast radio and television transmitter sites in the UK[a] (AGNIR 2012)

Service class	Effective Radiated Power (kW)[b]						
	0–0.1	**>0.1–1.0**	**>1–10**	**>10–100**	**>100–500**	**>500**	**Total Number of sites**
Analogue TV	406	59	36	14	12	5	532
Digital TV	6	10	11	26	3	0	56
DAB	3	74	130	0	0	0	207
VHF/FM Radio	150	79	81	23	17	0	350
MW/LW Radio	3	56	21	11	4	0	95

[a] Data collected from the following websites in October 2011:
http://www.bbc.co.uk/reception/transmitters
http://www.aerialsandtv.com/digitalnationwide.html

[b] True radiated power is conventionally quoted for MW/LW radio and is given here

2.2.2.1.1 Long, medium and short-wave bands

In the long and medium wave bands, antennas tend to be formed as tall metal towers with cables strung between them and attached to the ground around them. Often, a single LF or MF radiating structure may involve several towers located closely together and fed in such a way that a directional beam pattern is formed. Some towers are energised and insulated from the ground, while others are grounded with no power feed and act as reflectors. Transmitters designed to provide local radio services, e.g. around cities, use powers in the 100 W to 10 kW range, while a small number of transmitters providing national services over large distances radiate up to a few hundred kW (Table 2.3).

The HF (short-wave) band is used for international broadcasting and the wavelengths are somewhat shorter than those in the long and medium wave bands. Curtain arrays, composed of multiple horizontal dipole antennas suspended between towers, are used to form narrow beams directed upwards towards the required azimuth and elevation angles. The beams reflect off the ionosphere and provide services to distant countries without the need for any intermediate infrastructure. Typical curtain arrays can be up to 60 m tall and wide, and might, for example, involve 16 dipoles arranged as four vertically stacked rows of four with a reflecting wire mesh screen suspended behind them. Given the transmission distances, the radiated powers (actual power, not ERP) are high, typically around 100–500 kW. The HF band has the fewest transmitters of any of the broadcast bands. For example, Allen et al. (1994) reported a total of 25 HF transmitters with powers in the range 100–500 kW and three with powers above 500 kW in the United Kingdom.

Broadcast sites can be quite extensive, with multiple antennas contained within an enclosed area of several km^2. A building containing the transmitters is located somewhere on the site and RF feeder cables are laid from this building to the antennas. On HF sites, switching matrices allow different transmitters to be connected to antennas oriented towards different directions according to the broadcast schedule. Sometimes the feeders are enclosed in coaxial arrangements and sometimes they are open, e.g. as twin lines having pairs of conductors around 15 cm apart suspended around 4 m above ground level.

In considering reported measurements of RF EMFs at MF/HF broadcast sites, it is important to note that workers may spend much of their time in offices, workshops or the transmitter halls. Such locations can be far from the antennas, resulting in exposure levels are much lower than when workers approach the antennas to carry out maintenance and installation work.

Jokela et al. (1994) investigated the relationship between induced RF currents flowing through the feet (both together) to ground and the RF EMF strengths from MF and HF broadcast antennas. The MF antenna was a 185 m tall base-fed monopole transmitting 600 kW at 963 MHz. At distances of 10, 20, 50 and 100 m from the antenna, the electric field strength at 1 m height was around 420, 200, 60 and 30 V/m respectively. At the same distances, the foot currents were around 130, 65, 30 and 10 mA. The HF antenna was a 4×4 curtain array suspended between 60 m towers and radiating 500 kW at 21.55 MHz. The total field in front of the antenna at 1 m height ranged from around 32 V/m at 10 m through a maximum of 90 V/m at 30 m, a minimum of 7 V/m at 70 m and thereafter rose to around 20 V/m at distances in the 100–160 m range.

Mantiply et al. (1997) has summarized measurements of RF EMFs from MF broadcast transmitters contained in several technical reports from the mid-1980s to early 1990s from US government agencies. A study based on spot measurements made at selected outdoor locations in 15 cities and linked to population statistics showed that 3% of the urban population were exposed to electric field strengths greater than 1 V/m, while 98% were exposed above 70 mV/m and the median exposure was 280 mV/m. RF EMF strengths were also measured near eight MF broadcast antennas, one operating at 50 kW, three at 5 kW and four at 1 kW. The measurements were made as a function of distance along three radials at most of the sites. At distances of 1–2 m the electric field strengths were in the range 95–720 V/m and the magnetic field strengths were in the range 0.1–1.5 A/m, while at 100 m field strengths were in the ranges 2.5–20 V/m and 7.7–76 mA/m.

Mantiply et al. (1997) also included field measurements near short-wave (HF) broadcast antennas. As mentioned earlier, these are designed to launch beams upwards at low elevation angles. Hence, the field strengths at locations on the ground are determined by sidelobes from the antennas and vary unpredictably with distance and from one antenna to another. Measurements were made at four frequencies in the HF band and at six locations in a community around 10 km from an HF site, which was likely to have transmitted 250 kW power. Electric and magnetic field strengths at individual frequencies varied in the ranges 1.5 to 64 mV/m and 0.0055–0.16 mA/m, while the maximum field strengths just outside the site boundary were 8.6 V/m and 29 mA/m. Field strengths measured at a distance of 100 m along a “traverse” tangential to the beam from a curtain array transmitting at 100 kW were in the ranges 4.2–9.2 V/m and 18–72 mA/m. A final set of measurements were made at a distance of 300 m from another curtain array transmitting at 100 kW while the beam was steered through ±25° in azimuth. The field strengths were in the ranges 1.7–6.9 V/m and 14–29 mA/m.

2.2.2.1.2 VHF and UHF Bands

The powers used for broadcasting in the VHF and UHF bands vary widely according to the area and terrain over which coverage is to be provided (Table 2.3). UHF transmissions are easily affected by terrain, and shadowed regions with poor signal strength can occur, e.g. behind hills and in valleys. For this reason, in addition to a main set of high power transmitters, large numbers of local booster transmitters are needed, which receive the signals from the main transmitters and rebroadcast them into areas in shadow. The main transmitters are mounted at the top of masts up to several hundred metres tall and have Effective Radiated Powers (ERPs) up to around 1 MW, while the booster transmitters have their antennas mounted much nearer to the ground and mostly have powers lower than 100 W. VHF signals are less affected by terrain and fewer in-fill transmitters are needed.

Typical high power broadcast transmitter masts are shown in Figure 2.10. Figure 2.10a shows a 368 m concrete-tower with a spherical structure just above the 200 m level. This is accessed by lifts from ground level and contains various equipment as well as a public restaurant. The radiating antennas are above the sphere and the antennas operating at the highest frequencies are nearest to the top. Multiple dipole antennas protrude through the wall of the red/white cylinder to provide FM radio services in band II, and TV and DAB services in band III. Contained within the top-most section of the tower are the band IV and V antennas for more TV services.

a) b)

Figure 2.10. Typical antenna towers for high-power broadcasting of radio and television signals.

Figure 2.10b shows a steel lattice tower with the TV antennas in the white cylinder at the top. Antennas for VHF and DAB broadcast radio services are mounted on the outside of the tower just below the TV antenna and there are multiple antennas for other communications purposes at lower heights. The transmitters are in a building near the base of the tower and the coaxial cables carrying the RF to the transmitting antennas pass up inside the tower.

Access to the antennas on high power VHF/UHF masts is gained by climbing a ladder inside the tower, and reaching the antennas at the top of the tower involves passing in close proximity to radiating antennas at lower heights, as shown in Figure 2.11. The VHF transmissions have wavelengths of similar dimensions to the structures that form the tower itself, e.g. the lengths of the steel bars or the spaces between them, and hence tend to excite RF current flows in these items. Standing waves can be present within the tower, and the measured field strengths can be strongly affected by the presence a person making measurements. Thus, field strength measurements can seem unstable and difficult to interpret. Currents flowing within the body can be measured at the wrist or ankle and these are more directly related to the SAR (dose) in the body than the fields associated with the standing waves. Hence, body current measurements can be preferable to field strength measurements on towers with powerful VHF antennas.

Several papers discussed by ICNIRP (2009) have reported measurements in the 10s to 100s of V/m range within broadcast towers, but it is not clear how representative these spot measurements are of typical workers' exposures. Cooper et al. (2004) have used a body-worn broadband instrument to measure electric and magnetic field strengths during work activities at a range transmitter sites. They reported that a wide temporal variation in exposure was typically found within any single electric or magnetic field strength exposure record obtained from work on a mast or tower used for high-power VHF/UHF broadcasts. Figure 2.12 shows a typical trace that was recorded during work activities near the VHF antennas while climbing on a high power VHF/UHF lattice mast. The field strength commonly ranged from below the detection threshold of around 14 V/m to a level approaching or exceeding the upper detection limit of around 77 V/m. The highest instantaneous exposures usually occurred when the subject was in the vicinity of high-power VHF antennas or when a portable VHF walkie-talkie radio was used to communicate with co-workers.

Figure 2.11. A worker climbing a ladder inside a triangular section lattice mast with TV broadcast antennas at the top. VHF broadcast dipole antennas are mounted just beyond the reflecting square mesh screens on the faces of the mast. The pipe-shaped structures are the coaxial feeders carrying the TV signals from the transmitters on the ground to the antennas at the top of the mast.

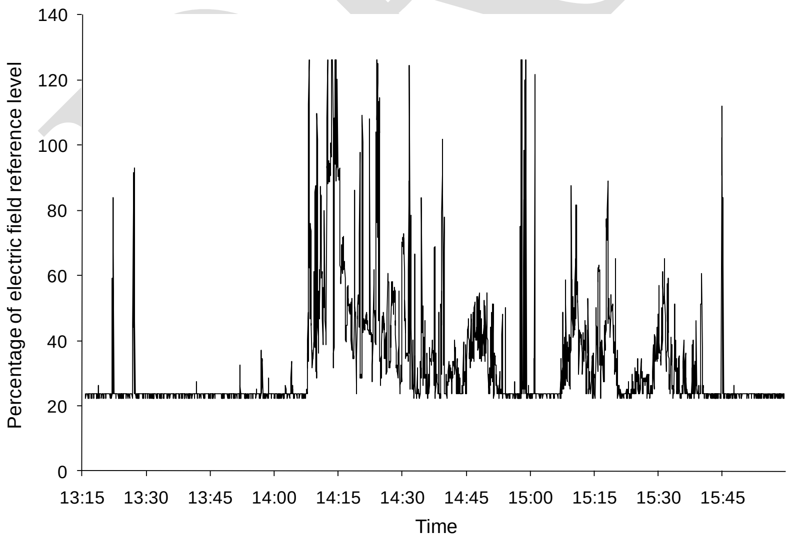


Figure 2.12. Electric field strength recorded for an engineer operating on a mast supporting antennas for high-power VHF/UHF broadcast transmissions. The "reference level" is 61 V/m, as taken from the ICNIRP (1998) exposure guidelines for workers over the relevant frequency range (10–400 MHz).

Electric field strengths around the foot of towers/masts have also been reported and seem quite variable. Mantiply et al. (1997) describes values in the range 1–30 V/m for VHF TV, 1–20 V/m for UHF TV and 2–200 V/m for VHF FM radio sites. Certain designs of antennas have relatively strong downward-directed sidelobes, known as grating lobes, which is a possible explanation of the variability.

VHF/UHF broadcast antennas are designed to direct their beams towards the horizon, usually in all directions about the tower. Hence, field strengths at ground level and in communities near the tower are much less than at comparable distances within the beam. The beams do reach ground level eventually, but they have spread out considerably by such distances, again implying general public exposures that are substantially lower than those at locations accessible to workers, as summarized above.

Mantiply et al. (1997) refers to studies of population exposure in the US conducted during the 1980s and based on spot measurements at selected outdoor locations. 50%, 32% and 20% of the population were estimated to be exposed above 0.1 V/m from VHF radio, VHF TV and UHF TV signals respectively. 0.5% and 0.005% were exposed above 2 V/m from VHF radio and TV respectively, while 0.01% were exposed above 1 V/m from UHF TV. One of the original publications (Tell & Mantiply, 1980) further explains that the measurement data underpinning the analyses comprised approximately 14,000 measurements of VHF/UHF broadcast field strengths made at 486 locations throughout 15 large cities over more than a 3-year period. The median population exposure level (VHF and UHF combined) was 50 $\mu W/m^2$ and around 1% of the population were exposed above 10 $\mu W/m^2$.

VHF/UHF radio and television broadcast signal field strengths were measured at 200 statistically distributed locations in residential areas around Munich and Nuremberg in Germany (Schubert et al., 2007). The interest of the study was in whether the levels had changed as a result of switch-over from analogue to digital broadcasting, and the measurements were made before and after this occurred at each location. The median power density was 0.3 $\mu W/m^2$ (11 mV/m) for the analogue signals and 1.9 $\mu W/m^2$ (27 mV/m[1]) for the digital signals. FM radio signals had median power densities of 0.3 $\mu W/m^2$ (11 mV/m), similar to the analogue TV signals, and the values ranged over approximately two orders of magnitude either side of the medians for all types of broadcast signal. It is interesting to note that these measurements seem lower than those found in the US during the 1980s.

2.2.2.2 Cellular radio networks

Unlike broadcasting, where high power transmitters are used to cover large areas extending 100 km or more from the transmitter, cellular radio networks employ large numbers of low power transmitters, known as base stations, scattered throughout an area where coverage is to be provided. Many base stations are needed because the communications are two-way (duplex) in cellular networks, with each user needing their own dedicated communications channels, both for the uplink (mobile to base station) and for the downlink (base station to mobile). The base stations are connected together and into the wider telecommunications networks through point to point radio links or buried cables/fibres.

An important consideration in the design of cellular networks is that the operators have a limited amount of spectrum available and have to reuse their frequency channels to provide coverage everywhere. A typical frequency map illustrating how coverage can be provided with 12 frequency channels is shown in Figure 2.13. Signals using the same frequency in different cells can potentially interfere with each other, but signal strength reduces with increasing distance from base stations and frequencies are not reused in adjacent cells/sectors. Hence, services can be provided without interference provided the radiated powers of mobiles and base stations are minimised.

Power minimisation occurs by allocating a maximum power output that can ever be used by each base station according to its own individual circumstances. It also occurs through the process of Adaptive Power Control (APC) through which the output power of phones and base stations is varied dynamically during calls such that no more power than is necessary is used at any given time. Power minimisation has important consequences for the RF exposures of people using mobile phones and living near base stations that are explained later in this chapter. In particular, it implies that worst case assessments of exposures based on maximum output powers theoretically possible may be considerably higher than the exposures that typically occur in practice.

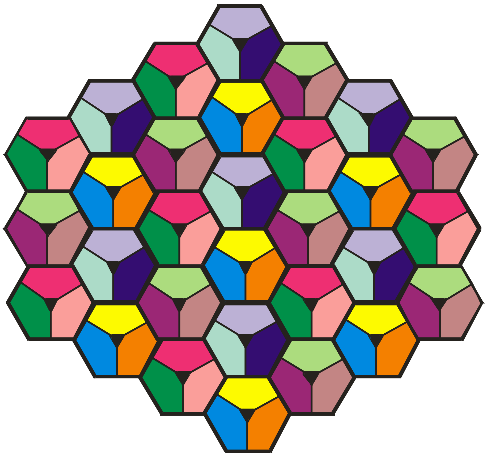


Figure 2.13. Example coverage plan for a cellular network. Each cell is hexagonal, with a base station at its centre and configured to provide signals over three 120 degree sectors. The colours show how coverage is provided everywhere using 12 frequency channels, none of which are used in adjacent cells

Each base station has limited capacity in terms of the number of users it can serve simultaneously so the transmitters are closer together where is a high density of users. In sparsely populated areas the transmitters may be around 10 km apart, whereas they may be apart by a hundred metres or less in locations such as city centres where there is a high density of users.

Networks may be organised with different layers of coverage such that cells of different sizes overlap but use different frequency channels. *Macrocell* base stations provide the main coverage in a cellular network and tend to have their antennas mounted on tall masts and above buildings in order to have a clear view of a large area. *Microcells* tend to be mounted at lower heights and provide street-level coverage in urban areas. *Picocells* typically provide indoor coverage where there are large numbers of people, e.g. in shopping centres and sports venues. *Femtocells* tend to provide coverage in a single office or open indoor space.

2.2.2.2.1 Technology generations

Developments in cellular radio technology are broadly categorised according to four different generations. First generation networks serving mainly car phones were rolled out in a few locations from around 1980. Hand-held phones and more widespread services became available from the mid-1980s. First generation systems included Advanced Mobile Phone System (AMPS) in North America, Total Access Communication Systems (TACS) in much of Europe, Nippon Telegraph and Telephone (NTT) and JTACS/NTACS in Japan, and Nordic Mobile Telephony (NMT). The systems were based on analogue technology and used frequency modulation to deliver voice communication services. These networks mostly closed down from around the year 2000, as users moved to later generations of the technology.

Second generation networks (2G) started from the early 1990s and continue to operate. They are based on digital radio technology and use voice coding to improve spectral efficiency. Many systems use Time Division Multiple Access (TDMA) within their frequency channels; such systems include Global System for Mobile (GSM) in Europe, Personal Digital Cellular (PDC) in Japan, and both Personal Communication Systems (PCS) and D-AMPS (digital AMPS, also known as "TDMA") in North America. Other North American systems are known as CDMA, because they use Code Division Multiple Access. Second generation systems were extended after their introduction to include some basic data services, but later systems with enhanced data services are usually termed 2.5G.

The third generation of mobile phones (3G), with comprehensive data services, became available in the early 2000s. These phones have developed to become today's "smart phones," although it is important to recognize that they are fully backward-compatible with 2G networks, and whether 2G or 3G is used at any given time depends on network coverage and how operators have chosen to manage call/data traffic within their network. The systems use CDMA radio access methods.

A fourth generation of the technology (4G) is being rolled out to meet increasing demand for data services and a fifth is under discussion. Some 4G systems are known as LTE (Long-term Evolution) and use

OFDM (Orthogonal Frequency Division Multiplexing), while others are based on Wi-Max. As with 3G services, this technology is being overlaid with other existing services, and phones are able to support multiple access modes (4G, 3G and 2G) without the user necessarily being aware of which is in use at a given time.

The frequency bands originally used by cellular networks in various parts of the world are shown in Table 2.4. However, it is important to note that spectrum liberalization is presently occurring, where an operator who holds a license for a particular part of the spectrum may choose to use it to provide services with any technology they wish. For example, bands originally reserved for 2G services such as GSM are being made available for 3G/4G services in many countries as demand shifts from 2G to systems with more capacity for data services. Also, with the move to digital television broadcasting, spectrum in the range 698 to 854 MHz is becoming available and being reallocated from broadcast to cellular services.

Table 2.4. Frequency bands originally used by different mobile phone systems (adapted from IARC (2013)).

Generation	Service start[a]	Main region	System[b]	Handset Band MHz	Base Station Band MHz	Channel Spacing kHz
1	1979	Japan	NTT	925 – 940	870 – 885	25
1	1981	Nordic countries	NMT450	453.5 – 457.5	463.5 – 467.5	25
	1986		NMT900	890 – 915	935 – 960	12.5
1	1985	Europe	TACS/ETACS	872 – 915	917 – 960	25
1	1989	Japan	JTACS	915 – 925	860 – 870	25
	1989		NTACS	898 – 901 918.5 – 922	843 – 846 863.5 – 867	12.5
1	1985	Germany	NET-C	451.3 – 455.74	461.3 – 465.74	20
1	1985	USA & Canada	AMPS	824 – 849	869 – 894	30
	1985		N-AMPS	824 – 849	869 – 894	10
2	1992	USA & Canada	TDMA800	824 – 849	869 – 894	30
	1998		TDMA1900	1850 – 1910	1930 – 1990	30
2	1992	Europe	GSM900	890 – 915	935 – 960	200
	1993		GSM1800	1710 – 1785	1805 – 1880	200
2	2001	USA & Canada	GSM1900 (PCS)	1850 – 1910	1930 – 1990	200
2	1993	Japan	PDC900	940 – 956	810 – 826	25
	1994		PDC1500	1429 – 1465	1477 – 1513	25
2	1998	USA & Canada	CDMA800	824 – 849	869 – 894	1250
	1997		CDMA1900	1850 – 1910	1930 – 1990	1250
3	2001	World	IMT-2000 (W-CDMA)	1920 – 1980[c]	2110 – 2170[c]	5000
4	2009	World	LTE	Many possible	Many possible	Various

[a] The services will have started on a different date in each country

[b] For abbreviations see Cardis et al. (2011) and Singal (2010).

[c] Based on a 2001 technical standard. Later standards evolved to provide for the use various frequency bands.

2.2.2.2.2 Mobile phone base stations

The base stations that provide services to mobile phones come in many different sizes and shapes, according to their individual coverage requirements. Some examples are shown Figure 2.14. The cylinder at the top of the lamp-post style mast contains omni-directional radiating antennas, while the pill-box shaped object on the ceiling in the shopping centre is a microcell base station.

Figure 2.14. Mobile phone base station antennas: a lamp-post style mast by the side of a street and a ceiling-mounted antenna in a shopping centre

The maximum radiated powers and heights of mobile phone base station antennas are highly variable. Cooper et al. (2006) gathered height/power data from all the United Kingdom cellular operators, a total of 32 837 base stations around the year 2002 and these are shown in Figure 2.15. The figure shows base station total radiated powers typically varied from around 0.1 W to 200 W and that heights ranged from around 3 m to 60 m above ground level. There was a large population with heights around 15–25 m range and powers in the 20–100 W range, and a second population with heights around 2–6 m and powers of around 2 W. Cooper et al. concluded that the first population is likely to serve macrocells and provide the main coverage for cellular networks, while the second population is likely to serve microcells and provide a second layer of in-fill coverage, e.g. in densely populated areas.

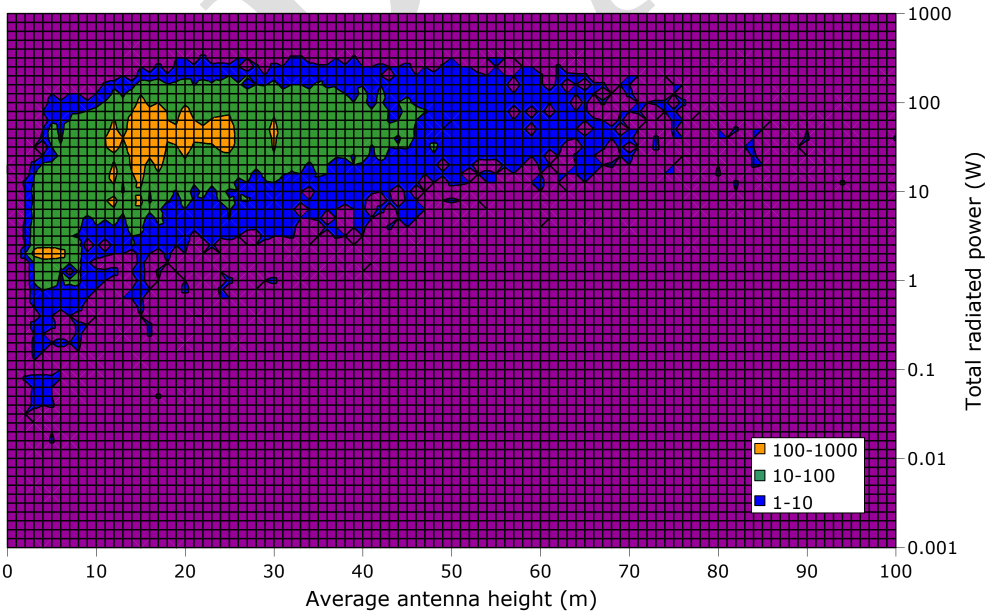


Figure 2.15. Distribution of 32 837 United Kingdom base stations according to average antenna height and total radiated power. The number of base stations is represented by a logarithmic colour scale. The bin separation parallel to the x-axis is 1 m. The y-axis is logarithmic and the bin separation parallel to this axis is a factor of $10^{0.1}$, ie 1.26.

Petersen and Testagrossa (1992) published some early measurements of power densities around analogue base station sites in the USA transmitting in the frequency range 869–894 MHz. A basic start-up site would serve a cell up to 12–16 km range and provide up to 16 signals (each serving one phone call) from a single omnidirectional antenna. As demand grew, sites could be expanded to split cells into three sectors with up to six antennas mounted on a triangular mast head. Again, each antenna would provide up to 16 signals so there was a maximum of 96 signals available, 32 of which would have been directed into each sector. Nominal ERP-values were around 100 W and so the radiated power would have been of the order of 10 W per signal from omnidirectional and sectored sites, having typical antenna gains in the range of 9–10 dB and 8–12 dB respectively. The measurements were made at intervals along radials from the bases of the masts out to distances of a few hundred metres for four masts ranging from 46 to 82 m in height. Individual signals from a given antenna were found to vary in strength at any given measurement position and the sidelobe structure of the antennas was evident in that the signal strength had an oscillatory dependence on distance. The maximum power density per signal was less than 100 $\mu W/m^2$ except in proximity to metal structures near the foot of the towers. Thus, even for 96 signals transmitted simultaneously the maximum aggregate power density possible would have been less than 10 mW/m^2.

Public concerns about mobile phone base stations became prominent from around the mid-1990s, as their number grew rapidly and individual transmitter sites became closer to communities. Some countries responded to concerns about exposures by setting up measurement campaigns to provide quantitative data for use in risk communication strategies and to confirm compliance with applicable exposure restrictions. Some of these programmes involve measurements at a sample of sites, e.g. in response to requests by communities, while others involve measurements being made as an integral part of commissioning or modifying all base station sites. Websites have been developed that make the gathered exposure data available to the public, e.g. by clicking on a map showing transmitter locations. In addition, technical reports and peer-reviewed papers have been published containing measurement data.

Across the national measurement programmes a variety of approaches to the selection of sites and measurement locations have been adopted, and several different measurement protocols have been used. Hence, some care is necessary in drawing comparisons between data arising from different countries. In particular, certain protocols involve sweeping a measurement antenna through a region of space and over a period of time, while recording the maximum exposure value that occurs. In general, the results from such procedures will be higher than those from procedures that seek to average the exposure over a region of space that might be occupied by a person and over a period of time sufficiently long to provide a repeatable measurement in the presence of signal fading (Section 2.1.5). Also, some procedures may have restricted measurements to locations where members of the public spend appreciable amounts of time, e.g. rooms inside buildings, while others may have sought to identify the maximum exposure possible at any location the public could ever access. Given these differences between approaches, the statistical distribution of reported measurements from different countries would not be expected to be the same, even though the network architectures and the conditions under which the populations are exposed may be similar.

Rowley and Joyner (2012) have gathered together data from measurement campaigns in 23 countries around the world from around the year 2000. The data included measurements from the following types of base station: AMPS800, CDMA800, ETACS, GSM900/1800, NMT, PCS1900 and WCDMA. Some countries had used narrowband equipment, generally based on spectrum analysers, while others had used less sensitive broadband equipment. Where narrowband equipment had been used, Rowley and Joyner found that it was difficult to compare the results from surveys that had used the equipment in different ways, e.g. with different measurement bandwidths and using different time-averaged vs peak hold modes. The data from 21 of the countries are summarised in Figure 2.16 and are based on over 173,000 individual data points. The global average exposure level, as shown in the figure was 0.73 mW/m^2, which is over 5000 times below the most restrictive value of the ICNIRP (1998) public reference level over the frequency range considered, i.e. 4 W/m^2 at 800 MHz.

Figure 2.16 shows clear differences between the data sets and average values from different countries. Rowley and Joyner (2012) ascribed these to the use of different measurement equipment and different approaches to selecting the measurement locations. Overall, the use of broadband equipment gives rise to higher average exposure values, which Rowley and Joyner explain is because each measurement made using it comprises the summation of multiple radio signals over a wide measurement bandwidth, whereas narrowband measurements are taken for each signal individually. However, it is also likely that broadband equipment would have been used at locations where it was anticipated that higher exposures would be found. For example, the broadband measurements from the USA were made on roof tops near to antennas. The measurements from the

UK arose from a very sensitive measurement system that reported many low values, which accounts for the low average in that country. Moreover, because the measurements from the UK country comprise around 70% of the measurements in total, this will have drawn the global average (reported above) downwards from what it would have been had the UK data been neglected.

As mentioned above, the data gathered from the various national measurement programmes included measurements ascribed to base stations of particular technologies. Rowley and Joyner (2012) performed analyses of the data gathered from 16 of the countries using only narrowband techniques in order to identify if differences were apparent. The results are reproduced in Figure 2.17 and, as with the data partitioned according to country, there are differences between the mean values for technologies, but the ranges of each dataset overlap substantially. Aside from three limited datasets that gave lower average values, all of the technology averages were within about a factor of 10 of 1 mW/m^2. Data for 4G (LTE2600) base stations arose only from Sweden and were one of the sets that had a lower average value.

Rowley and Joyner (2012) also analysed the data they had gathered to identify whether it provided evidence for exposures increasing or reducing over time and whether there was evidence of differences between measurements reported for base stations of particular technologies. The data according to year of measurement are shown in Figure 2.18 for the UK, USA, Spain, Greece and Ireland. The data sets all have substantially overlapping ranges and show no clear evidence of either an upward or a downward trend over time. Rowley and Joyner describe the limited variation as “striking”, given that the number of users grew substantially over that period, e.g. from 42.9 to 77.5 million in the UK and 50.9 to 283.1 million in the USA. While there is no evidence of an upward trend in the data analysed some caution is necessary in drawing conclusions with regard to population exposures. Each measurement in these data sets has been made close to a base station of particular interest, and that base station will generally dominate the measured value such that signals from other base stations will be negligible, even if their number and cumulative contribution to the exposure total has increased over time. To draw conclusions about population exposures would require measurements focused on individuals rather than sources.

To include figure 1 from
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3347802/

Figure 2.16. Minimum (•), maximum (•) and narrowband average (●), broadband average (○) or mixed narrowband/broadband average (■) of all survey data for each country with the number of measurement points for the country in brackets. For comparison, the global weighted average marked with dot-dashed line through (◊) and the ICNIRP reference levels for the public at 900 and 1800 MHz are also plotted (Rowley & Joyner, 2012).

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http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3347802/

Figure 2.17. Minimum (•), maximum (•) and average (●) for each wireless technology. For comparison, ICNIRP reference levels for the public at 900 and 1800 MHz are also plotted. Mobile Other refers to mobile technologies either not identified in the source survey or not included (e.g. PDC) in one of the other mobile technologies categories. All Mobile is the result of averaging over all mobile technologies. Only narrowband measurements (from 16 countries) could be used. The weighted averages for all available measurement years for each country were then averaged over the number of countries with measurements for each mobile technology. The figure in brackets on the horizontal axis label is the number of countries for which measurements were available for each technology (Rowley & Joyner, 2012).

To include figure 2 from
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3347802/

Figure 2.18. Minimum (•), maximum (•) and average of the narrowband measurements for the UK (●), Spain (■), Greece (▲) and Ireland (♦) and the broadband measurements for the US (○), with the year of measurement data on the horizontal axis. Note that not all years were available in all countries. For comparison, the ICNIRP reference level for the public at 900 MHz and 1800 MHz are included (Rowley & Joyner, 2012).

Mann (2010) also summarized the exposure data arising from the national audit programme of UK base stations performed by Ofcom (the UK's radio spectrum regulator) up the end of 2007. The data comprised measurements made at 3321 locations across 541 sites, comprising 339 schools, 37 hospitals and 165 other locations. For each location, an aggregate exposure value was formed by summing together the exposure contributions from each base station signal present in the narrowband data. Exposure quotients describe the fraction of the ICNIRP general public reference level (ICNIRP - International Commission on Non-ionizing Radiation Protection, 1998) that the signals measured collectively contribute and these are shown in Figure 2.19 as a cumulative distribution. Note, the analysis by Rowley and Joyner above treated each signal measured by Ofcom separately.

Figure 2.19 includes a lognormal curve fitted optimally (least squares) to the data. This suggests the data are approximately lognormally distributed, although with a longer tail towards the lower quotient values. The median exposure quotient value was 8.1×10^{-6} (around 8 millionths of the guideline reference level) and the range in the data from 5th to 95th percentile was from 3.0×10^{-8} to 2.5×10^{-4}. Around 55% of the measurements were made outdoors and these had higher exposure quotients than the indoor measurements. The median quotients for the outdoor and indoor measurements were 1.7×10^{-5} and 2.8×10^{-6} respectively, i.e. the outdoor median was around six times higher.

The studies above have been based on measurements made at particular sites of interest to those carrying out the assessments. Estenberg and Augustsson (2014) have adopted a different approach in developing a vehicle-based mobile monitoring system to gather field strength data over the frequency range 30 MHz to 3 GHz using narrowband equipment. The system was driven through urban, rural and city areas of Sweden and the position of each measurement made was identified from GPS co-ordinates. The authors found it was possible to completely map a small town with 15,000 inhabitants in a single working day (08:30 to 18:30). The focus of the work was on proving the measurement system and no mathematical corrections were made to interpolate or extrapolate the data to ensure uniform spatial sampling intervals, or to link the data to population density. However, over 70,000 measurements were gathered at the system's sampling interval of 370 ms. The median power densities found were 0.016 mW/m^2 in rural areas, 0.27 mW/m^2 in urban areas and 2.4 mW/m^2 in city areas. Base stations and mobile phones gave the dominant contribution to these totals. As with the spot measurements compiled by Rowley and Joyner (2012) in Figure 2.16, individual measurements were found to be extremely variable; a range of more than five orders of magnitude was found in the accumulated data over a driving distance of 10 km. The global average exposure level of 0.73 mW/m^2 derived by Rowley and Joyner lies between the values found by Estenberg and Augustsson (2014) for urban and city areas, which seems plausible, given that the majority of measurements made globally will have been in such areas.

Another group of studies that provide information relevant to environmental exposures are those that have used personal exposure meters worn for periods up to several days by groups of volunteers. These studies are covered separately in section 2.3. As with the study above by Estenberg and Augustsson above, they provide information not only on exposure from base stations, but also on exposure from other environmental, domestic and personal transmitters during everyday activities.

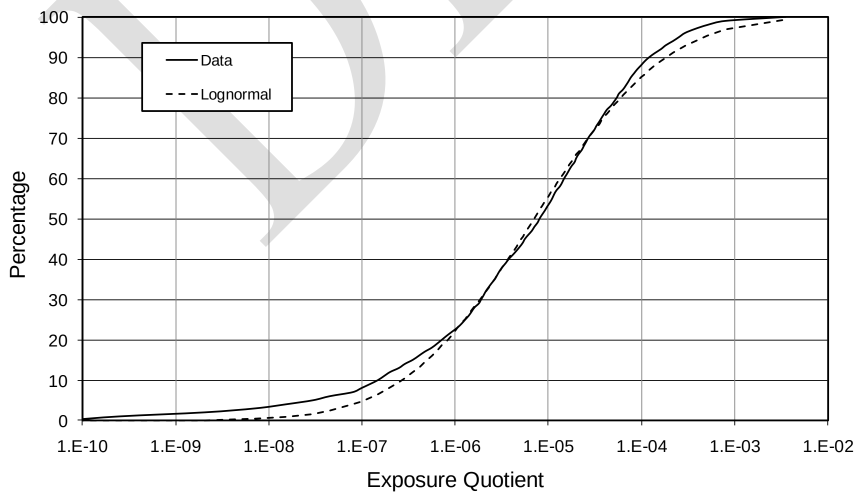

Figure 2.19. Cumulative distribution of exposure quotients corresponding to 3321 spot measurements made by Ofcom at 499 sites where people were concerned about nearby base stations with a lognormal curve fitted to the data (Mann, 2010).

2.2.3 Domestic and indoor transmitters

There are few powerful RF sources in the home, aside from microwave ovens and the situation is similar in most offices. However, there are increasing numbers of lower power sources in enclosed environments. These are mainly used for communication purposes and include wireless networks (Wi-Fi), base stations for cordless phones, baby monitors, and remote controlled toys. Note, cordless phones are described as "personal transmitters" in section 2.2.4. As with the section on environmental transmitters, this section does not seek to cover all types of transmitters that might conceivably be present in homes, but focuses on those that are most numerous and where published data on exposures is available.

2.2.3.1 Wireless networks

Wireless networking has developed rapidly since around the year 2000 and is becoming the method of choice for connecting mobile devices such as laptop computers and mobile phones to other electronic systems and the internet. The networks are found in homes, schools, public places such as cafes and transport hubs, and in the workplace. The systems operate to the IEEE 802.11 family of technical standards and are often known as Wi-Fi, after the Wi-Fi Alliance, an organization that certifies interoperability of devices on the market.

The original version of IEEE802.11 was published in 1997 and provided for data rates up to 2 Mb/s using frequency channels between 2.4 and 2.5 GHz. Subsequent developments using this band were IEEE802.11b and IEEE802.11 g, allowing for rates up to 11 and 54 Mb/s respectively. Several frequency bands between 5 and 6 GHz are exploited by IEEE802.11a and provide for 54 Mb/s communications. The standard continues to develop, with the most recent versions allowing for the simultaneous use of several separate frequency channels and providing for data rates up to around 1 Gb/s.

The IEEE 802.11 standard allows for devices with maximum radiated powers of up to 1000 mW, but this is above the level permitted by spectrum regulatory agencies in certain parts of the world. For example, in Europe the technical standards EN300328 and EN301893 limit the equivalent isotropic radiated power to 100 mW in the 2.4 GHz band and 200 mW in parts of the 5 GHz band respectively.

Peyman et al. (2011) measured the actual power radiated during transmission by a selection of Wi-Fi devices marketed towards United Kingdom schools. The spherically-integrated radiated power (IRP) ranged from 5 to 17 mW for 15 laptops in the 2.4 GHz band and from 1 to 16 mW for eight laptops in the 5 GHz band. For practical reasons, and because access points are generally wall mounted with beams directed into the rooms, their powers were integrated over a hemisphere. These powers ranged from 3 to 28 mW for 12 access points at 2.4 GHz and from 3 to 29 mW for six access points at 5 GHz. Thus the radiated powers of laptops seem to range from a few mW up to around 20 mW. In principle the measurements imply the powers of access points could range from a few mW up to around 60 mW, if their patterns extend symmetrically into the unmeasured hemisphere, but this seems unlikely.

The RF emissions from Wi-Fi devices are in the form of short bursts containing portions of the data being transmitted and other information such as acknowledgements that data have been successfully received. Unlike the emissions from mobile phones using TDMA, the bursts are irregular in terms of when they are produced and their durations. Typical bursts range from around ten microseconds to around 1 millisecond in duration. If data are lost or corrupted during transmission, e.g. as a result of radiofrequency interference from other devices, bursts are retransmitted until they are successfully received. Also, under conditions where communications are poor, e.g. due to weak signal strength at the receiver, the systems can lower their data rates to ones that provide better signal to noise ratios and improved reliability. This increases the time that it takes to transmit a given amount of data. Thus, high signal strengths from Wi-Fi devices (during transmission of bursts) do not necessarily translate to higher time-averaged exposures because good communication conditions result in shorter transmission times for individual bursts and can reduce the number of bursts that have to be retransmitted.

Khalid et al. (2011) has reported results for the temporal characteristics of emissions from Wi-Fi equipment in school networks based on over the air data traffic monitoring and add-on devices used with laptops to accumulate their total transmit time duration. The gathered data were examined to determine the proportion of time individual Wi-Fi devices transmitted while children were using laptops normally as part of their lessons. The laptops were mostly being used for receiving traffic from the access points (downloads) and therefore laptop transmit times were low. Duty factors of the monitored laptops were consistently below 1% and those of access points, generally mounted on the wall or ceiling of the classrooms, were below 10%. Baseline duty factors of access points (with no data being transferred) are around 1% due to beacon pulses of 1 ms duration that are produced at a rate of ten per second (Mann, 2010).

The importance of realistic assessment of exposure to WLAN sources has been highlighted by Joseph et al. (2013), where they noted a considerable overestimation of exposure when duty factor is assumed to be 100% (worst case approach). In a typical scenario (30 cm away from an access point with high speed connection of 54 Mbps), and considering 100% duty factor, the measured field value would be 11 times below the ICNIRP (1998) reference level, whereas considering a more realistic duty factor of 6.1%, the field value would be 45 times below the reference level.

The SAR values produced when using laptop computers equipped with Wi-Fi transmitters have been evaluated by several authors. Most devices now have built-in antennas located around and along the top edge of the screen, which are therefore at greater distances from the body than a mobile phone held against the head. The rapid reduction in field strength that occurs with increasing distance means that SAR can be expected to be much less than from mobile phones. Based on a continuous radiated power of 100 mW under a range of such scenarios, Findlay and Dimbylow (2010) calculated a maximum 10 g averaged SAR in the head of 5.7 mW/kg and concluded this represents less than 1% of the SAR previously calculated in the head for a typical mobile phone exposure condition based on the results of Martínez-Búrdalo et al. (2004). Accounting for transmit powers of real Wi-Fi devices being less than 100 mW (as per the work of Peyman et al. above) and typical duty factors occurring during normal use would increase this margin still further.

Scenarios where Wi-Fi devices are able to transmit continuously with their antennas in close proximity to the body can lead to higher SARs than the scenario described above. For example, Kühn et al. (2007) measured an SAR of 0.81 W/kg in a flat phantom with the antennas of a Wi-Fi access point in close proximity and Schmid et al. (2007b) measured 0.05 W/kg under similar conditions from a Wi-Fi equipped PCI card inserted into a laptop. The value of Kühn et al. (2007) is within the range of maximum localized SARs from mobile phones (see section 2.2.4.1).

Studies have also examined the field strengths generally in the environment where Wi-Fi networks are installed. Foster (2007) measured RF EMFs at 55 public and private sites in the USA and Europe (4 countries), which included private residences, commercial spaces, health care and educational institutions. In nearly all cases, the measured Wi-Fi signal levels were far below other RF signals in the same environment. The maximum time-averaged power density in the 2.4 GHz band measured at 1 m from a laptop uploading and downloading a file was 7 mW/m^2, which is far below the ICNIRP (1998) reference level value of 10 W/m^2 for general public.

Schmid et al. (2007a) investigated the typical exposure caused by WLAN applications in small sized (internet café) and large sized (airport) indoor public areas. Outdoor scenarios were also considered where the exposure was assessed in the environment of access points serving residential areas and public places. The exposure was assessed both by computational methods and on-site measurements. The highest values of indoor exposure were found close to the transmitting devices (access points or clients) where at a distance of around 20 cm, spatial and temporal peak values of power density were found to reach around 100–200 mW/m^2. In general, the exposure values were several orders of magnitude below ICNIRP (1998) reference levels.

2.2.3.2 Smart meters

A new RF source that is presently being rolled out and which seems set to be used at many homes is the transmitter associated with “smart” metering of electricity use, and potentially the use of other services such as water and gas. Smart meters are intended to provide more detailed information about resource usage to suppliers and consumers alike. This will enable near real-time billing of customers and facilitate a move towards distribution systems that can be more responsive to demand. Ultimately, some devices could be controlled remotely, e.g. washing machines, so they run at times when surplus capacity is available or energy less costly.

There is no globally harmonised approach to gathering the information from smart meters and relaying it back to the utility companies through a wide area network (WAN), but it is clear that radio communications will be involved in many systems. Some systems may use mobile phone networks for their WAN, in which case the meters at people’s homes will have similar technical characteristics to mobile phones, and send data using communications protocols such as text messaging. Other WAN systems may use dedicated radio infrastructures, including mesh systems in which the meters in a locality relay the signals from one to another in order to reach a central collection point.

In addition to the WAN, some systems may also involve a home area network (HAN), which transmits usage data from the smart meter to a portable read-out device used by the householder, thereby enabling them to examine the information and make decisions about their own energy usage. In some systems the HAN can also enable individual "smart" electrical devices within the home to be controlled and relay information about their own usage/status to the householder.

Recent investigations (Tell et al., 2012) suggest that radio transmissions from smart meters will be at a similar power level to mobile phones, but that the duty factors will be low (they will transmit for a small proportion of the time on average). Tell et al. concluded that all peak measurements even those at 0.3m from a smart meter face, were below FCC MPE for general public. Zhou and Schneider (2012) also suggested that low duty factors, combined with the greater distances of the smart meter devices from people than mobile phones, imply that exposures will be low in relation to exposure guidelines.

Comment: Additional reference to be discussed in to this section (Foster & Tell, 2013)

2.2.3.3 Microwave ovens

Microwave ovens are standard fixtures in many homes and contain microwave sources operating at a frequency of 2.45 GHz and producing powers in the range 500 W to 2 kW. The design is such that leakage should be kept to a minimum, and a product performance technical standard requires that microwave power density levels have fallen below 50 W/m^2 at 5 cm distance. Several large surveys of leakage levels have been performed, as described in ICNIRP (2009), and these indicate that approximately 99% of ovens comply with the emission limit. Bangay and Zombolas (2003) measured the maximum localised (10 g) SAR from an oven operating under conditions equal to the emission limit as 0.256 W/kg and estimated that the maximum whole-body averaged SAR would be 0.0056 W/kg at a typical operating distance of 30 cm.

2.2.4 Personal transmitters

This section summarises information about the exposures produced by devices carried on the person and which transmit in immediate proximity to the body. Such sources include mobile and cordless phones, professional radio communications terminals such as those used by the emergency services

2.2.4.1 Mobile phone handsets

The maximum output powers and, where TDMA is used, also the burst characteristics of various types of mobile phones are summarized in Table 2.5. Analogue mobile phones were specified to have maximum EIRPs (defined in section 2.2.2.1) of 1 W, but the antennas were not isotropic and would have had gains similar to a simple dipole, i.e. around 2 dB. This implies the radiated powers would have been around 600 mW. Second generation mobile phones using TDMA have time-averaged powers that were less than their peak powers according to the duty factors. For example, GSM phones that transmit at a power level of 2 W in the 900 MHz band (GSM900) have time averaged powers that are 12% of this, i.e. 240 mW[1]. Maximum time-averaged output powers are generally in the range 125–250 mW for the second generation onwards.

[1] This is based on a frame structure in which 1 of 8 slots is allocated to a given user and every 26th allocated slot contains no transmission, i.e. $1/8 \times 25/26$.

Table 2.5. Maximum output powers and TDMA characteristics of various types of mobile phones

System	Peak Power, W		Burst duration ms	TDMA Duty Factor	Average Power W
	EIRP	Output			
NMT450	1.5	0.9		N/A	0.9
NMT900	1.0	0.6		N/A	0.6
TACS/ETACS	1.0	0.6		N/A	0.6
AMPS/NAMPS	1.0	0.6		N/A	0.6
TDMA800		0.6	6.666	1/3	0.2
TDMA1900		0.6	6.666	1/3	0.2
PDC		0.8	3.333 or 6.666	1/6 or 1/3	0.133 or 0.266
CDMA800		0.25		N/A	0.25
CDMA1900		0.25		N/A	0.25
GSM900		2.0	0.5769	0.12	0.24
GSM1800		1.0	0.5769	0.12	0.12
PCS1900		1.0	0.5769	0.12	0.12
IMT-2000		0.25		N/A	0.25

2.2.4.1.1 SAR values

Mobile phones are generally held with their transmitting antennas around 1–2 cm from the body so the RF EMFs they produce are highly non-uniform over the body and diminish rapidly in strength with increasing distance. The fields penetrate into the body tissues, leading to energy absorption, which is described by the specific absorption rate (SAR). SAR values are derived by phone manufacturers under a series of prescribed tests and the maximum recorded under any of the tests is reported in product literature. The maximum SAR values in normal usage positions should be lower than the values declared by manufacturers because the positions used in the testing standards are designed to identify near worst case conditions. Figure 2.20 shows a compilation of SAR data published by manufacturers and obtained according to European measurement standards.

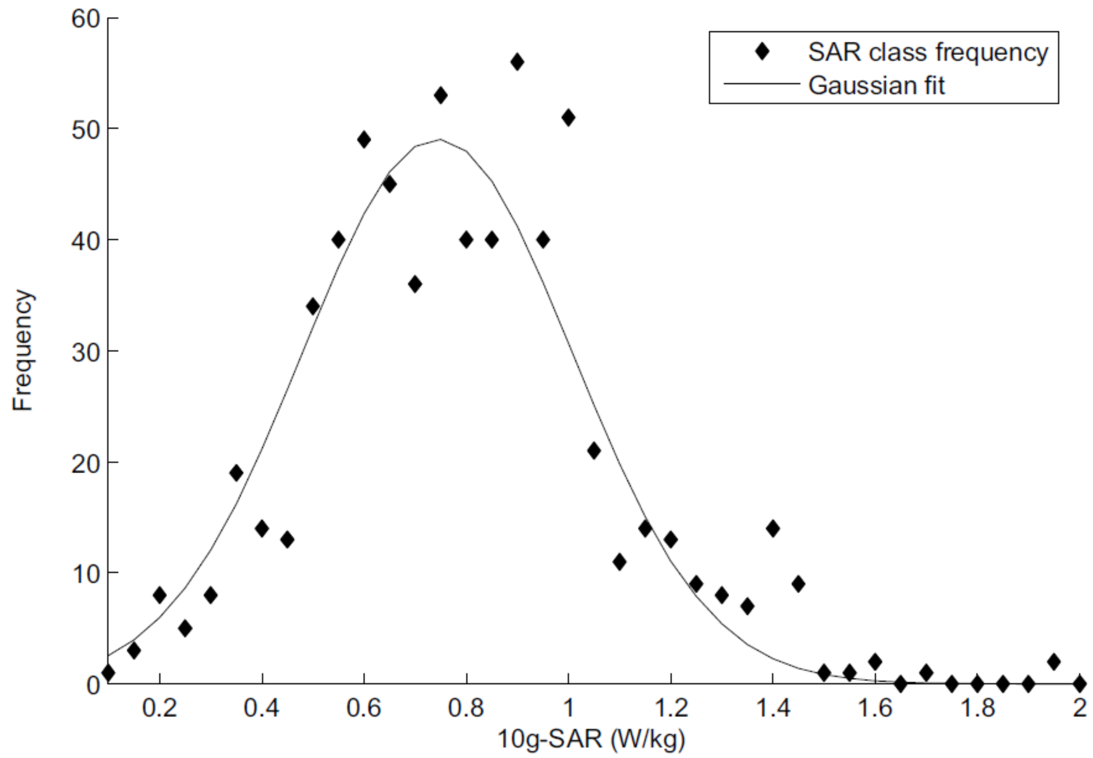

Figure 2.20. Statistical distribution of maximum 10 g averaged measured for 668 mobile phones according to standard EN50361 (CENELEC, 2001). Data from German Federal Office for Radiation Protection, in Kühn & Kuster (2007).

Table 2.5 gives the maximum output powers for different types of phones, but as explained in section 2.2.2.2, the actual power used at any time during a call is variable up to this maximum because of adaptive power control is used. Vrijheid et al. (2009) found that the reduction was on average to around 50% of the maximum with GSM phones, and Gati et al. (2009) found 3G phones only operated at a few percent of the maximum power.

A further consideration is that GSM phones employ a mode called discontinuous transmission (DTX) under which their transmission burst pattern changes to one with a lower duty factor during the periods of a conversation when a mobile phone user is not talking. Wiart et al. (2000) found that DTX reduced time-averaged power by about 30% for GSM phones.

As shown in Table 2.5, analogue mobile phones had higher specified maximum radiated powers than digital ones (typically 0.6 W vs 0.1–0.25 W). While these systems are no longer in use and there is little exposure data available, it is of interest to consider whether exposures would have been higher with these phones than with present day ones. Key differences, aside from relative power levels, are that analogue phones were larger than their modern digital counterparts and that they had generally larger antennas, e.g. extractable whip antennas rather than the compact helices and patch antennas used nowadays. The increased distance of the antenna from the head would have reduced the SAR level overall and the larger size of the antenna would have led to a more diffuse distribution of SAR in the head. These aspects are discussed further in Chapter 3.

The evolution of localized SAR over time is also interesting to consider. Cardis et al. (2011) assembled a database of reported peak 1 g and 10 g SARs for phones from a range of publications and web sites. The majority of the data covered the period 1997–2003 and no significant upward or downward trends over time were found within data for the 900 or 1800 bands.

Thus, in summary, the spatial peak SARs do not seem to have changed significantly over time as analogue phones have been replaced by digital ones. However, the more diffuse nature of the distributions produced would likely have led to a greater overall SAR in the head, including the brain.

2.2.4.1.2 Phones not making calls

The emitted powers from phones when they are on standby and not making calls are also of interest. Few studies have been published on this topic, but transmissions are brief and infrequent, as is necessary to prevent large numbers of inactive phone users placing a significant burden on the networks. Time-averaged output power, and therefore potential exposure of people, is expected to be much less than during voice calls.

Hansson Mild et al. (2012) considered the use of ordinary mobile phones as sources of exposure in biological experiments and explained that a GSM phone in "stand-by" mode is only active when updating its location information with the network. When the phone is stationary, their study found this occurred with a frequency set by the net operator, typically every 2-5 h in Denmark, and that the location update involved a series of short burst emissions over a duration of about 2 s. When moving with the phone, the updating occurs for each hand-over from one base station to the next. Between the location updates, the phone was a passive radio receiver with no RF emission. The authors suggested that since the experimental period in most of the exposure investigations is typically 30 min, the exposure from a phone in stand-by mode is in all practical aspects the same as sham exposure since exposure for a few seconds every few hours is negligible as far as average absorbed energy is concerned.

Urbinello and Röösli (2013) studied the personal exposure from GSM and UMTS phones (disabled phones as reference, dual band and quad-band smart phones) in stand-by mode in moving settings such as on public transportation (buses and trains) and cars. They found that the frequent hand-overs of phones from one base station to the next resulted in much more frequent transmissions than when stationary phones are on standby. Also, when surrounded by many other users with their phones on standby, as in a train carriage, the cumulative effect of hand-over transmissions can give an appreciable contribution to exposure. They recommended that these exposures should be taken into account in epidemiological studies. The authors reported that UMTS uplink exposures were considerably lower than GSM uplink exposures and that quad band phones seemed to use both the GSM and UMTS frequency bands for location updates. They also suggested that, in a car, one's own mobile phone is a relevant source of exposure to passengers. The authors however cautioned against generalisation of their results as they reflect a snapshot in time based on one type of mobile phone for each scenario and two mobile phone operators.

Phones equipped for data services (smart phones) such as e-mail will transmit for more of the time than ordinary phones because they will be synchronising data, e.g. emails, held on the phone with remote servers. Also, uploading large files such as video and photographs may take many minutes. A phone is unlikely to be held against the head while this is taking place, although it may be in the pocket or elsewhere on the body, which may lead to emissions at a higher power level than during calls, e.g. if GPRS is used, involving multislot transmission with GSM.

Text messaging involves a short period of transmission from mobile phones when the messages are sent. Gati et al. (2009) showed that the longest text message possible with GSM systems would take 1.5 seconds to send.

2.2.4.1.3 Hands free kits and Bluetooth earpieces

Sometimes phones are used with wired hands free kits (HFKs), in which case the phones may expose parts of the body other than the head to maximal localized SARs, e.g. if they are placed in a pocket during calls. While one might expect that the audio cable to the ear-piece would not guide RF EMFs to the ear-piece efficiently, and that the use of wired HFKs would lead to greatly reduced SARs in the head as the phone would be further away, there have been suggestions that this is not always the case.

Porter et al. (2005) showed that the layout of the HFK cables was a critical factor in determining head exposures and that certain geometries could result in appreciably more power being coupled into the audio cable than others. However, in all of the combinations tested, use of a HFK resulted in a lower maximum 10 g SAR value than without one. Kühn et al. (2009) further developed procedures for the testing of HFKs under worst case and realistic usage conditions and applied them to a set of phones and HFKs. It was concluded that use of HFKs reduced exposure of the entire head compared to use of a phone directly against the head, but that there might be very localized exposure enhancements in the ear.

Wireless HFKs are also available that use the Bluetooth RF communications protocol to link to a mobile phone handset somewhere within a few metres of the body. This protocol provides for RF transmissions in the frequency range 2.4–2.5 GHz at power levels of 1, 2.5 or 100 mW. Only the lowest of these power levels would be used with a wireless HFK and these powers are around a hundred times lower than the maximum output powers of mobile phones. In the work on wired HFKs mentioned above, Kühn et al. (2009) also tested Bluetooth wireless HFKs and concluded that they exhibit a low but constant exposure.

2.2.4.2 Terrestrial Trunked Radio (TETRA)

TETRA is a cellular radio system designed with the needs of professional users and the emergency services in mind. The handsets can be used like mobile phones, but it is more normal to use them walkie-talkie style held in front of the face and in push to talk (PTT) mode. Remote speaker microphones, ear-pieces and a variety of covert add-ons are also available. When the handsets are used with accessories, the transmitting handset may be mounted on the belt, on the chest or elsewhere on the body. Systems for use in vehicles with the transmitting antennas mounted externally are also available. The operating principles and the detailed characteristics of the signals involved are described in a review by AGNIR (2001).

Several frequency bands are available between 380 and 470 MHz as well as one set of bands near 900 MHz. Handsets can have peak emitted powers of 1 W or 3 W and vehicle mounted transmitters can have powers of 3W or 10 W. Base stations have similar powers to those used for mobile phone networks, i.e. a few tens of watts. The system uses TDMA, although the frame rate is slower than the TDMA systems involved with mobile phones. There are four slots per frame and there are 17.6 frames per second. Hence, the bursts from handsets occupy slots of duration 14.2 ms and the time averaged power is a quarter of the peak powers mentioned earlier in this paragraph. The base stations transmit continuous signals.

The AGNIR review refers to SARs measured in a model of the head from a 3 W handset and from a 10 W handset held to either side of the head and in front of the face. With spatial averaging over 10 g, as per ICNIRP and IEEE exposure guidelines, the 1 W radio produced SARs of 0.88, 0.89 and 0.24 W/kg on the left, right and front of the face respectively, while the 3 W radio produced 2.88, 2.33 and 0.53 W/kg for the same conditions.

Dimbylow et al. (2003) developed a numerical model of a commercially available TETRA handset and calculated SARs in a 2 mm resolution anatomically realistic numerical model of the head developed from MRI images. The handset was modelled as a metal box of dimensions 34 × 50 × 134 mm, and with either a helical (pitch 4 mm, diameter 8 mm) or a monopole antenna mounted on its top face and resonant at 380 MHz. For the handset held vertically in front of the face in the position that was considered to be most representative of practical use, the 10 g averaged SARs were 1.67 W/kg and 2.37 W/kg per watt of radiated power with the monopole and helical antennas respectively. Various positions were considered with the handset held to the sides of the head and the maximum SARs with the two antennas were 2.33 and 3.90 W/kg per watt. These values suggest SARs with 3 W handsets (3/4 W time-averaged) having a helical antenna could exceed the 2 W/kg restriction on general public exposure, if they were to transmit at full power for six minutes while held to the side of the head.

2.2.4.3 Cordless phones

Cordless phones are used to make voice calls and they are held against the head in a similar way to mobile phones. Hence, the antenna inside the phone is in close proximity to the head and its radiated fields deposit energy inside the head tissues near to the phone in a similar way to the fields from mobile phones. The communications are over shorter distances than with mobile phones and so lower radiated powers are used, but the phones do not use adaptive power control and so, unlike mobile phones, they do not continually adapt their radiated power to the minimum necessary for satisfactory communications.

With simple cordless installations, the phones are typically placed back on a desk or charging point after a call has finished. However, there are also more complicated installations where multiple base stations are installed throughout a building and the phones are carried as personal phones. The phones in these larger systems have their own unique number. The radio communications are typically over distances of a few tens of metres and to nearest base station, which provides the link into the main wired telephone system.

The first cordless phones used analogue technology and operated to a range of different technical standards with continuous emitted power levels of around 10 mW during calls. Frequencies were generally in the 30–50 MHz range and therefore around 20 times lower than the frequencies used by mobile phones. Some phones used telescopic antennas of around 15–30 cm length, while others used helical antennas of around 5 cm length. The lower frequencies and the greater size of the antennas used with analogue cordless phones would have resulted in a smaller proportion of the radiated power being absorbed, and also a more diffuse pattern of absorption, in the head than occurs with mobile phones.

Modern cordless phones use digital technology, including the Digital Enhanced Cordless Telephony (DECT) technical standard which operates in the frequency band 1880–1900 MHz and is the main system used in Europe. Systems operating around 900, 2400 and 5800 MHz are used in other parts of the world, as well as DECT.

DECT systems produce discontinuous emissions due to their use of time division multiple access (TDMA). The signals from the phone and base station during calls are in the form of 100 bursts every second, each of around 0.4 ms duration. These bursts are emitted at a peak power level of 250 mW, but the time-averaged power is 10 mW because each device only transmits for 1/24 of the time (duty factor of 4%). Handsets do not transmit unless calls are being made, but most base stations produce 100 beacon pulses, each of 0.08 ms duration, per second when on standby. This implies a duty factor of 0.8%.

2.2.4.4 Professional mobile radio

A variety of professional mobile radio systems have been developed over the years and these are generally licensed to professional users by spectrum management agencies in the countries where they are used. In many countries the emergency services (police, fire, ambulance etc) are moving to mainly use digital cellular systems, such as TETRA, but analogue systems are also used and were the norm before roll-out of TETRA systems.

The systems use frequencies in the VHF and UHF parts of the spectrum, and VHF generally propagates further for a given radiated power and so is preferred for longer distance communications. UHF systems, on the other hand, have smaller antennas and therefore form more compact terminals.

Systems exist in the form of walkie talkies that are held in front of the face and used in push-to-talk (PTT) mode, as systems built into vehicles with external, e.g. roof-mounted, antennas and as covert systems that can be worn discreetly on the body. The transmitting antennas can be on the handset, on the chest or waist, on a vehicle of concealed inside clothes.

The radiated powers are typically in the 1 to 5 W range, but it is important to take into account the duty factor associated with how they are used, e.g. PTT mode will involve a few seconds of transmission at a time while the button is held in and the user speaks.

2.2.5 Industrial applications

There are several industrial applications of radiofrequency electromagnetic fields, many of which are described in review reports and papers. On the whole, the literature is rather old and a difficulty in interpretation is that reported field values have generally been taken in the context of compliance assessments rather than epidemiological studies. As such, the data represent maximum exposures likely to occur during normal use of the equipment and it is difficult to judge what typical exposures of workers may have been. Notable technical reviews containing data about sources and exposure levels include those by Allen et al. (1994) and Cooper (2002). Only a brief description of some of the sources producing the highest exposures is included here.

2.2.5.1 Induction heating

Industrial induction heating involves the use of induction furnaces containing large coils that produce strong magnetic fields. Conducting materials for treatment are placed inside the coils and the magnetic fields cause eddy currents to flow, with the result that the materials are heated up. Typical applications include surface hardening, softening and melting metals, mixing alloys and heating gaseous conductors such as plasmas. The frequencies used span a wide range, from 50 Hz through to a few MHz, so not all applications fall within the scope of this monograph. The fields can be considerable and worker exposures are greatest with tasks that involve approaching the coils, e.g. when taking samples from within the coils of open furnaces. The coil impedances increase with frequency and electric fields can become the dominant contributor to exposure (rather than magnetic fields) at frequencies above around a hundred kHz. Allen et al. (1994) have provided a review of measured exposures, drawing on earlier peer-reviewed papers from several countries and previously unpublished measurements made in the United Kingdom.

2.2.5.2 Dielectric heating

Radiofrequency (RF) heating and drying equipment has been used for many years and applications include pre-heating, wood-gluing and PVC welding. These materials are lossy dielectrics and their conductivity at radiofrequencies means that they can become heated up when placed in a strong electric field. Typical heaters are designed to use the ISM (Industrial Scientific and Medical) license-free frequency bands at 13.56, 27.12 and 40.68 MHz, but reported measurements (Allen et al., 1994) show more variable frequencies within the 10–80 MHz range. Powers range from less than a kilowatt to a few kilowatts.

The greatest source of operator exposure results from the use of manually actuated PVC dielectric machines, where the operator manipulates material to be welded by hand and then clamps it between a pair of electrodes between which the RF power is applied. Measurements and other details from studies carried out in the United Kingdom and other countries are described by Allen et al. (1994).

The fields from dielectric heaters at the operator locations can be in excess of the ICNIRP (1998) reference levels, but they are non-uniform and it is necessary to evaluate the SAR in the body to determine compliance with the guidelines. Kännälä et al. (2008) has developed an assessment method based on measuring induced limb currents and relating these to localized and whole body SARs.

Another consideration when assessing exposures is that the welding operations are often of shorter duration than the 6-minute averaging time that applies when assessing exposure in the context of the ICNIRP exposure guidelines. Compensating the measurements to account for duty factor in use can therefore be a means of showing compliance with guidelines.

2.2.6 Medical applications

RF EMFs are used in several medical applications, which involve moderate heating of tissue for therapeutic purposes, or much greater heating for the cutting and destruction of tissues during surgery. Magnetic resonance imaging also involves the application of strong RF EMFs while scans are being performed. In general, the RF sources will be further from clinicians than their patients, which will result in lower exposures than for the patient, but this is not always the case.

2.2.6.1 Magnetic resonance imaging

Magnetic resonance imaging uses a combination of EMFs to produce exceptionally clear images of tissue structures inside the human body to assist with medical diagnoses. The system works by causing hydrogen atoms associated with water in the body tissues to resonate such that they emit RF radiation at the resonant frequency. Variations in the water concentration in tissues are therefore the basis on which contrast is produced in images.

A permanent uniform static magnetic field, typically in the 1–3 T range, but sometimes up to 8 T or more with specialized systems, is applied over the body and causes splitting of the energy states associated with protons (hydrogen atoms). The difference between the energy states is such that protons will transfer from the lower energy state to the upper one in response to an applied RF signal at the resonant frequency. They will also decay back to the lower state spontaneously, and in doing so emit RF EMFs at the larmor frequency. The larmor frequency is given by 42.57 times the static magnetic field strength. Thus a 1.5 T MRI scanner involves the application and measurement of RF fields at 64 MHz.

During an MRI scan multiple RF pulses (hundreds to thousands per second) are applied over either the whole body or a part of the body being imaged. The RF dose (SAR) received by patients inside MRI scanners is reported by the systems and can vary from less than 0.1 W/kg to about 4 W/kg for more complex settings (HPA, 2008). The desire to limit temperature rises and prevent harm to the patient can be a limiting factor in how quickly scans can be performed in practice.

Clinicians and other people who are near to the magnet during the scans will be exposed to the RF EMFs, but the strength of the fields will reduce rapidly with increasing distance from the RF coils and the space between them inside the scanner.

2.2.6.2 Diathermy

Short wave and microwave diathermy are used to provide gentle heating to muscles, tendons and joints to alleviate a variety of medical conditions. Short wave equipment operates at 13.56 MHz or 27.12 MHz and powers of around 400 W. Applicators for microwave diathermy operate at 2.45 GHz with powers of around 200 W and tend to be formed as a radiating antenna with reflectors around it to direct the energy in a forward direction. While exposure of the patient is intentional, operators may be close to the equipment and exposed in regions of high field strengths, unless they move away while the equipment is operating.

Comment: Additional reference to be discussed in this section (Shah & Farrow, 2013)

2.2.6.3 Surgical diathermy and RF ablation

RF EMFs and RF currents are widely used during surgical procedures. Surgical diathermy, or electrosurgery, uses a small hand-held electrode to act as a cutting or coagulation instrument. The fundamental operating frequency is typically around 500 kHz and there are harmonics produced at frequencies up to around 20 MHz. Current densities in tissues can be as high as 10 A/cm^2 (100 kA/m^2) with source powers up to 200 W (Grant et al., 2010).

Some more recent systems use 9.2 GHz and powers of around 20 W delivered through needle electrodes containing coaxial lines inside them. These are used with minimally invasive surgery, e.g. the probe tip can be inserted in a tumour and the heat used to destroy it, the systems are also used in the treatment of menorrhagia by endometrial ablation.

2.2.7 Security and article surveillance

Comment: Text under development – suggestions for references to be included would be welcomed

There are a variety of radiofrequency systems used for security purposes, and these include systems for asset tracking and identification as well as visualising objects. ICNIRP (2009) reviews these sources and exposures.

2.2.7.1 Electronic article surveillance

2.2.7.2 Body scanners

Whole-body security scanners are used in places such as airports in order to form images of objects carried under people's clothing without the need for physical contact. Active systems transmit either ionising (X-rays) or non-ionising (radiofrequency) radiation towards the body and then analyse the scattered radiation. Passive systems simply monitor the "black body" (thermal) radiation given off by the body in the radiofrequency spectrum (see section 2.2.1) and do not transmit RF radiation. Current active radiofrequency systems typically operate around 30 GHz, although future systems may use frequencies up to several hundred GHz (SCENIHR, 2012). A note published by AFSSET (2010) described an assessment of an active scanner operating in the frequency range 24-30 GHz. Power densities incident on the body were reported as between 60 and 640 µW/m^2.

2.2.7.3 Terahertz applications

2.2.8 Radar and navigation

Comment: Text under development – suggestions for references to be included would be welcomed

Radar systems operate across a broad range of frequencies, mostly in the 1–10 GHz range, with some short-range applications in the 10s of GHz range. Their emissions represent an extreme form of pulse modulation, the TDMA scheme used by some communications technologies being a less extreme example. For example, the duty factor in a GSM TDMA signal is 1/8, whereas it is typically around 1/1000 with a radar signal.

Systems vary widely, but a typical radar pulse duration might be around a microsecond and typical pulse period might be around a millisecond.

Very high power densities can be produced in the antenna beams during pulses, but in order to assess people's exposure it is important to decide whether the assessment should be based on the peak exposure during the pulse or the time-averaged exposure. The former is relevant for considerations associated with the microwave auditory effect, while the latter is relevant to whole-body and localised temperature rises.

In addition to the duty factor resulting from pulsing, there is a second duty factor to consider in assessing exposures from systems rotating in the plane of azimuth and producing narrow directional beams. Generally, the rotation period will be up to few tens of seconds in duration and therefore be much shorter than the 6-minute averaging period in the ICNIRP guidelines. Hence, rotation reduces time-averaged exposures in any given direction by a factor equal to 360° divided by the beamwidth in degrees.

Information about sources and exposures under this category can be found in the following review reports: Allen et al. (1994), Cooper (2002) and ICNIRP (2009). Joseph et al. (2012) have published a detailed review of occupational and public exposure from communication, navigation, and radar systems used for air traffic control.

2.2.8.1 Air traffic control radar

The most familiar application of radar is for navigation and the tracking of aircraft movements from rotating ground-based antennas, e.g. at airports. Long range systems operate in the 1–2 GHz range and moderate range ones operate in the 2–4 GHz range. The antennas tend to be mounted sufficiently high up that buildings cannot obstruct their view of the sky and they form narrow beams of around a degree in the horizontal plane which sweep around once every few seconds. Beams are broader in the vertical plane and tail-off in strength towards low elevation angles to avoid reflections from objects on the ground. Aviation radar systems have quite high emitted power levels during the pulses, typically in the 10s of kW to a few MW range. Taking the duty factors into account leads to time-averaged emitted powers of around 100 W to a few kW.

2.2.8.2 Marine radar

Marine radar systems are used in order that ships can be aware of the presence of other vessels and avoid collisions. The range is less than with aviation systems and it is known that targets will be at ground (sea) level so the beam profile extends to ground level in the plane of elevation. The rotating antennas are mounted high-up on vessels so they have a view of the sea that is unobstructed by the structure of the ship/vessel on which they are mounted. Operating frequencies are in the 2–4 or 8–12 GHz ranges. Mean powers are in the range 1 to 25 W and peak powers can be up to around 30 kW.

2.2.8.3 Tracking radar

Tracking radar is used in military systems to lock onto and follow targets such as aircraft and missiles. These antennas can rotate, execute a nodding motion, point in a fixed direction, or follow a target. Targets are not expected to assist with being tracked and may even be designed with stealth in mind and to suppress the extent to which they reflect radar pulses. Hence, tracking radar systems generally involve higher powers than navigation systems and use peak powers up to several MW. Systems mostly operate between 2 and 8 GHz.

2.2.8.4 Other radar systems

Various other radar systems include those used for monitoring weather, traffic speed, collision avoidance with vehicles and ground penetration.

2.2.8.5 Aircraft navigation (other than radar)

Comment: Section to include information about DVORs and NDBs etc

2.3 Environmental personal exposure assessments

Recent advances have been made in the capability of body-worn instruments for measuring the strengths of environmental radiofrequency signals (see section 2.4) during people's everyday lives. These personal exposure meters (PEMs) are now regarded as sufficiently robust and reliable for use in studies of exposure trends related to people's health. The use or sensitive receivers to make measurements in a number of selected narrow frequency bands where the most common sources transmit as led to detection thresholds on the most sensitive instruments of around 10 mV/m in terms of electric field strength. This is several thousand times below the ICNIRP reference level and within the typical range of environmental exposures (see section 2.2).

However, care is required in interpreting the readings from the PEMs and these have to be treated appropriately when developing exposure metrics in studies (Mann, 2010). The field strength at the body surface, where the instrument is present, is heavily perturbed and different from the field strength that would be found at the same location in the absence of the body. A rigorous calibration should therefore take account of the field perturbation by the body, although for the purposes of exposure categorisation in an epidemiological study, this might be ignored. The current generation of PEMs responds to the peak power of pulse modulated (TDMA) signals and this should be taken into account so that the contribution of pulsed signals such as DECT, GSM uplink and Wi-Fi to time-averaged exposure is not over-estimated in relation to continuous signals.

The quality of epidemiological studies can be improved by combining quantitative approaches based on measurement and computational modelling. The main investigation may also be supplemented by exposure validation studies and these have improved understanding of the merits and weaknesses of the various approaches taken. Personal exposure meters capable of logging exposure for a number of frequencies are now becoming available, although even these have limitations in terms of application in large scale studies (Radon et al, 2006), including achieving sufficient sensitivity to measure typical environmental fields and the development of standardised methods for data collection and analysis (Mann, 2010; Röösli et al., 2010).

2.3.1 Measurement experience and approaches

Comment: Text under development – suggestions for references to be included would be welcomed

2.3.1.1 Sensitivity aspects

The measurement data gathered with PEMs have proved to be highly variable, as with the spot measurement data of Section 2.2, and a substantial proportion of the data acquired have been below the detection limit (typically 50 mV/m) of the PEMs. Röösli et al. (2008) have developed a method for estimating the mean field strength based on an assumption of log-normality in the distribution of the data. This regression on order statistics (ROS) method seems to produce plausible estimates of the mean field exposure even when only a few values are above the detection threshold.

2.3.1.2 Population measurements

In general, the studies performed so far have taken the readings from the PEMs at face value and not considered implications about how the PEMs respond to the under-lying signal aspects. Hence, a degree of caution is necessary in interpreting any trends in relative exposure contributions identified in studies. In particular, any influence of DECT, Wi-Fi and GSM handset signals on mean exposures may have been over-estimated because these signals are of a TDMA nature with low duty factors. Also, signals that are only intermittently present, including those from GSM base stations that do not carry the broadcast channel, will be neglected if they are not present when the PEM takes its measurement sample.

2.3.1.3 Micro-environmental measurements

Comment: The exposure data in the following references are to be summarised in Section 2.3 above. Suggestions for additional references would be welcomed.

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Bürgi A, Frei P, Theis G, Mohler E, Braun-Fahrländer C, Fröhlich J, Neubauer G, Egger M, Röösli M (2010). A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. Bioelectromagnetics, 31(3):226-36.

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Joseph, Wout , Leen Verloock, Francis Goeminne, Günter Vermeeren, Luc Martens, "Assessment of general public exposure to LTE and RF sources present in an urban environment", Bioelectromagnetics Volume 31, Issue 7, pages 576–579, October 2010.

2.4 Exposure assessment

Comment: Text under development – suggestions for references to be included would be welcome

2.4.1 Instrumentation

Comment: Section to describe the different types of measurement instrumentation, highlighting strengths and weaknesses and including illustrations.

2.4.2 Protocols and standards

Comment: To briefly summarise published technical standards and measurement protocols and mainly provide a sign-post to where they can be found

2.5 Exposure systems for laboratory studies

Comment: References for this section are in a separate table at the end of the document.

A variety of experimental systems are used to assess the effects of RF exposure on live animals/humans (*in-vivo* conditions), as well as on excised tissue samples and cell cultures (*in-vitro* conditions). Purpose-made exposure systems provide a highly defined electromagnetic exposure to the sample under study, while avoiding interference from other environmental sources of exposure. These systems usually provide controlled environments in terms of temperature and in terms of physical, chemical and biological agent contaminants. Suitable experimental arrangements for the laboratory assessment of RF exposure have been widely reported (Guy et al., 1999; Kuster and Schönborn, 2000; Schuderer and Kuster, 2003; Zhao, 2005; Zhao and Wei, 2005).

Several factors affect the performance of the laboratory exposure systems, such as efficiency of the coupling between the incident field and the biological system, the number of animals or cell culture samples that can be exposed simultaneously, the daily exposure time, and overall duration of the study.

2.5.1 Exposure systems for animals and cell cultures

Some exposure systems are designed specifically for studies involving cell cultures and excised tissues. Whole and partial body exposure systems are also available for live animal studies to assess the effect of exposure from near field and far field sources. These systems are based on similar principles to the *in-vitro* systems; however, they additionally need to consider the requirements of live animals and variation in exposure caused by their movement.

Examples of laboratory exposure systems are: transverse electromagnetic (TEM) cells, RF anechoic chambers, radial transmission line (RTL), waveguides and wire patch cells (Ji et al., 2006; Pickard et al., 2000; Schönborn et al., 2000; Schuderer et al., 2004a; Schuderer et al., 2004b; Calabrese et al., 2006; Laval et al., 2000; Ardoino et al., 2004; De Prisco et al., 2008). Figure 2.5.1 shows a typical exposure system used with cell cultures.

Figure 2.5.1 RF exposure set up for cell cultures exposure to 1950 MHz EMF (continuous or modulated wave). The set up consists of a RF generator, an amplifier, a splitter and two power sensors; samples are exposed by means of a short-circuited waveguide hosted in a cell culture incubator.

Radial waveguides, TEM cells and anechoic and reverberation chambers are examples of whole body exposure systems (Chou et al., 1985; Chou and Guy, 1982; Ardoino et al., 2005; Balzano et al., 2000; Wilson, 2002; Wang et al., 2002; Faraone, 2006; Kainz, 2006, Jung et al., 2008; Schelkshorn et al., 2007; Tejero et al., 2005). Partial body exposure systems such as carousel and loop antennas consist of local devices targeting an animal's brain/head area (Swicord et al., 1999; Chou et al., 1999; Leveque et al., 2004; Schönborn et al., 2004; Wake et al., 2007; Lopresto et al., 2007).

Paffi et al. (2013) compared 52 different exposure systems that have been used for animal (*in vivo*) exposure studies. They categorised the systems according to the experimental protocol (whole-body or localised exposure), their electromagnetic characteristics (radiating, propagating or resonant) and whether they were for use with freely moving or restrained animals. Radiating systems, i.e. systems involving transmitting antennas, were the most frequently used systems and could produce high power efficiencies (1-50 W/kg per W) in the exposed organ of with restrained animals when using localised exposures in the near-field region. When exposure was produced at greater distances from the antennas, and in the far-field to give more uniform whole-body exposures, the power efficiency was lower (<0.05 W/kg per W) and generally decreased with increasing numbers of exposed animals. However, Paffi et al (2013) concluded radiating systems are easy to design and can be used above frequencies of 2 GHz provided anechoic conditions are present. Propagating systems based on waveguides, TEM and GTEM cells are used for whole-body exposures with restrained animals and offer better power efficiency (0.2-3 W/kg per W) than radiating systems. Radial transmission lines are particularly suited to exposing large numbers of animals, but the efficiency in such configurations is reduced to <0.1 W/kg per W. Resonant systems based on cavities with restrained animals have an efficiency of about 1 W/kg per W. Reverberating chambers allow for freely moving animals and offer efficiencies in the range 0.018-0.47 W/kg per W and Paffi et al. (2013) suggest they are suitable even for chronic, life-long exposures.

There is a need to develop exposure systems that can accommodate multiple exposures and exposures at frequencies above 3 GHz. There are several technical difficulties in designing such systems; nevertheless this has been one of the WHO's research priorities (WHO, 2010; 2006) as there are emerging communication protocols and technologies in frequencies between 3-9 GHz.

Comment: Reference to include as an example system providing for multiple exposures: Romeo et al 2013.

2.5.1.1 Transverse electromagnetic (TEM) cells

A TEM cell is a closed metal container that is shielded from external RF fields and through which an imposed electromagnetic wave propagates. The cells are usually rectangular in cross-section, with a non-tapered section in the middle and tapered sections on either side of the middle section, each leading to a coaxial aperture connected to an RF cable. RF is fed into the cell via one coaxial aperture and taken to an absorbing load from the other end of the cell, while the power flowing through the cell and absorbed by material in the cell is monitored.

The outer conductors of the two connecting cables join to the walls of the cell and the inner conductors are connected to a flat planar conductor inside the cell, known as the septum, which effectively separates the interior of the cell into two halves although a small gap is left between the septum and the cell walls. In such a structure the electric and magnetic field vectors are everywhere perpendicular to the direction of the wave propagation (transverse to it) and broadly equivalent to a uniform plane wave up to a certain maximum frequency determined by the cell dimensions (Crawford, 1974).

The tissue samples or cell cultures to be exposed are positioned inside the TEM cell in a defined orientation to the direction of an external electric field. An example of a typical TEM cell providing two exposure chambers separated by a septum is shown in Figure 2.5.2. The cell is vertically orientated with one tapering section at the top of the figure and the other hidden from view below the support stand. The two chamber doors are presently open and hinged down against the support stand. They would be closed during an experiment. As an example of a typical application, Nikoloski et al, (2005) have reported studies with cell cultures and animal models inside various modified TEM cells.

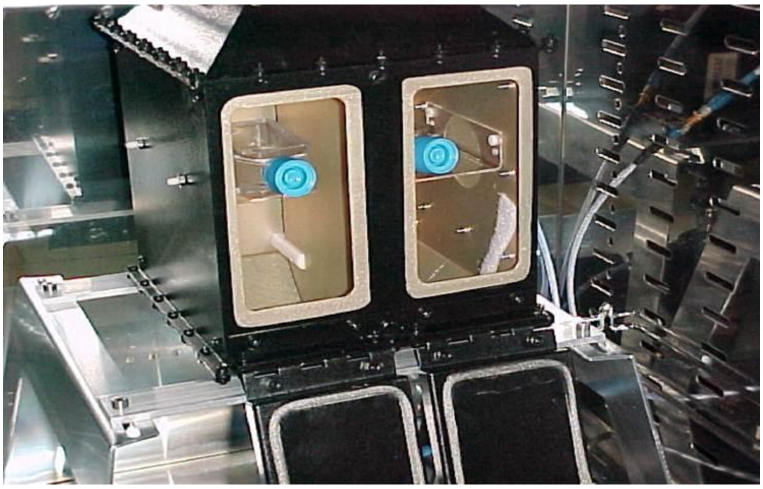

Figure 2.5.2 Transverse Electromagnetic (TEM) cells hosted in a cell culture incubator for in vitro exposures to 900 MHz EMF.

2.5.1.2 RF anechoic chambers

An RF anechoic chamber is a room with linings of RF absorbing material to minimise reflections of electromagnetic waves. Animals or cell cultures can be exposed inside the chamber to RF radiation emitted from an antenna.

2.5.1.3 Radial transmission line (RTL)

An RTL is a structure that confines an RF wave to propagate in two dimensions between two parallel metal plates excited between their centres by an antenna. The systems are used for both in-vivo and in-vitro studies by placing the cell cultures or animals at a fixed distance from the antenna where the exposure level can be calculated or measured subject to a given input power level.

In the case of a non-resonant implementation, the RTL is terminated at the perimeter of the lateral plates with absorbers (Moros et al., 1999 and Hansen et al., 1999). An RTL can also be implemented as a resonant structure by terminating the plate perimeters with metallic rods (reflectors) instead of absorbers. This configuration is called a "Ferris Wheel" in which the animals are placed in restraining tubes and positioned at a fixed distance from the reflecting rods (Balzano et al., 2000). It is also possible to produce non-uniform exposure scenarios in these structures by using multi modes that are excited by small deviations from symmetric loads (Ebert et al., 2009).

2.5.1.4 Waveguides

A waveguide is a structure that confines RF waves between its two endpoints (ports). A coaxial cable and the TEM cells mentioned above are examples of waveguides; however they both have centre conductors and can operate effectively to arbitrarily low frequencies. The waveguides described here have no centre conductor and are in the form of rectangular pipes with cross-sectional dimensions that determine their operating frequency range. The maximum operating frequency is usually somewhat less than twice their minimum (cut-off) frequency. Waveguides can be terminated by matched loads at their exit such that power flows through them without reflection, or with power fed in at one end and with a short-circuit at the other end such that the wave is reflected and the waveguide acts as a resonator. Figure 2.5.3 shows a collection of rectangular waveguides in an incubator, one of which is loaded with biological samples. A metal plate would be fixed over the open end of the waveguide during an experiment.

Figure 2.5.3 WR430, short-circuited waveguides in a cell culture incubator for EMF exposure at 1950 MHz. The upper waveguides are for RF exposure: up to four samples can be exposed at the same time to two different SAR values, hosted on a four-layer, vertical, plexiglass stand. The lower waveguide is for sham-exposure. All the waveguides are provided with customized tubes for the circulation of refrigerating water.

The waves that propagate inside rectangular waveguides are not in the form of plane waves and generally only either the electric field vector or the magnetic field vector remains transverse to the direction of wave propagation at all positions. Nonetheless, the fields inside rectangular waveguides are locally uniform and the exposure level of biological samples placed within the waveguides can be calculated subject to a given input power level.

Waveguides are widely used for in-vitro exposure scenarios (Schuderer et al., 2004b). for example, non-resonant waveguides have also been used to expose rodents (Guy, 1979) and a cascade of 17 sectorial resonant waveguides excited by one quad-loop antenna have been used to expose one rat per waveguide (Kainz et al., 2006).

2.5.1.5 Near-field systems

In near field exposure systems, RF antennas in close proximity are used to provide partial body exposure. For instance, in the so called "carousel system", the animals are placed in restraining tubes and radially oriented around a central antenna which is fixed in a known distance (Adey et al., 1999). For exposure to specific parts of the rodent brain, small loop antennas in immediate proximity to the head can be used (Leveque et al., 2004).

2.5.1.6 Reverberating chambers

Reverberating chambers are used when the exposure of unrestrained animals can be averaged over time. They are in the form of closed metal rooms/chambers that are highly shielded to minimise leakage of RF power. Rotating metal paddles (mode stirrers) cause the peaks and troughs in localised field levels within the room to shift through space over time with the result that the time-averaged field inside the chamber is much more uniform than the field would be at any point in time (Jung et al., 2008).

2.5.1.7 Wire patch cells

Paragraph to be added here in order to describe these systems

Figure 2.5.4 Wire patch cell (WPC) hosted in a cell culture incubator for *in vitro* exposures to 900 MHz EMF. The WPC id located inside a metal grid box, which provide electromagnetic shielding in order to avoid both electromagnetic compatibility problems, and interferences with the other WPC hosted in the same incubator.

2.5.1.8 Human exposure systems

Although the majority of the experimental dosimetry studies are carried out on animals, human exposure systems provide a useful tool to assess the exposure of volunteers to RF fields. For partial body exposure scenarios, commercially available telecommunication devices are usually modified so that they can be worn for the duration of the exposure without interruption, being isolated from other sources of exposure and also providing a blinded exposure environment (Boutry, 2008; Haarala et al., 2007; Krause et al., 2007; Loughran, 2005; Regel et al., 2006). Specially developed antenna systems have also been developed that simulate the exposure from commercially available telecommunication devices. These can be worn for long exposure durations during a whole day or overnight (Bahr et al., 2006). Some studies also involve whole body exposure conditions where a volunteer is placed in an anechoic chamber at a certain distance from a base station antenna for the duration of exposure (Regel et al., 2006).

2.5.2 Considerations for laboratory exposure systems

2.5.2.1 Near-field vs. far-field

Experimental studies often involve field measurements in the near field, which are difficult to perform because of the complex field components and coupling relationships with probes and any surrounding objects. External field measurements are at best only generally related to SAR in these situations, and there are additional uncertainties if the volunteers or animals are free to move. Ideally experimental work should involve a well-characterised exposure system and incorporate modern experimental and computational methods to determine the SAR, making use of more than one exposure level to allow a dose-response relationship to be investigated.

2.5.3.1 Metrology

Several exposure systems have been devised that allow excellent control of metrology and dosimetry, although some studies have simply used a commercial mobile phone to irradiate freely moving animals. This will produce highly variable exposures, especially to the head or testes, which not only depend on the animal's own behaviour and on social interactions between animals, but also on traffic on the local cellular network and on the network protocols. The use of such devices in experimental work should be avoided because of this lack of control if affords. Although far from ideal, it might be possible to use mobile phones as sources of exposure if it is possible to set them to produce emissions at a fixed frequency and output power using engineering or hardware controls. In animal experiments, there is often a necessary trade-off between the needs for accurate dosimetry and animal welfare. In most exposure systems there will be greater uncertainty in dosimetry with freely-moving animals, but preventing their movement will induce restraint stress which in itself could affect the outcome of the experiment. Hence the need for cage controls as well as sham-exposed animals, particularly in long-term studies. Reverberation chambers, however, offer the promise of providing good dosimetry without the need for restraint.

2.5.3.2 Reproducibility and interpretation of results

Several factors can affect the reproducibility of the laboratory exposure studies. These include; signal characteristics, polarisation of the induced field with respect to the biological system, field distribution, temperature increase and control of acoustic noise and ambient RF fields.

It is important that the performance of the experimental setup is tested by determination of the induced field strengths together with an uncertainty analysis to identify and quantify different sources of errors in the measurements.

Inclusion of a sham exposure group is also vital in interpreting the observed results in the exposed groups.

2.5.3.3 Laboratory animals

Studies carried out on laboratory animals, should take into account the type of species, strain, sex, age, weight, genotype, phenotype and exposure to other environmental agents. Animal's living condition, diet, treatment, cage material and restriction or availability of food, can affect the results of laboratory exposure studies.

Prevention of current flow to animals from water supply, positioning and orientation of the source of exposure, and movements inside the chamber should also be taken into account.

2.5.3.4 Cell cultures

Factors to be considered in exposure of cell cultures include: composition of the growth media, including antioxidant level, free radical scavengers and presence of magnetic particles. Cell type, species, strain, number of passages in culture, viability, growth phase, metabolic status, and cell density would also affect the outcome of the study. Environmental variables such as temperature, humidity, oxygen / carbon dioxide levels and air flow should be taken into consideration too.

2.6 Summary

Comment: To be developed later

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