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THE TECHNOLOGY OF MOBILE TELEPHONE SYSTEMS RELEVANT FOR RISK ASSESSMENT

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INVITED PAPER

Abstract — Mobile personal phones are now a mass market product, and considering that the general population is exposed to the electromagnetic fields around the telephone, it is of importance that the biological, medical and epidemiological community understands the basic technology. The most common access systems, FDMA, TDMA and CDMA, are reviewed with respect to the level and time variation of the power radiated from the antenna. The time variation has become of prime interest due to the biological effects noted from amplitude modulated radiations. The emphasis is on the low frequency variation of the high frequency power, and on the low frequency fields themselves.

INTRODUCTION

Mobile telephone systems show very large growth rates all over the world, and the penetration in some countries approaches 30%. It is expected that in the foreseeable future the total number of mobile phones will exceed the number of fixed telephones, and a large part of the population will thus be exposed to the electromagnetic fields surrounding a mobile phone. It is therefore understandable that concerns have been expressed about the possible health risks related to this exposure, and further, that extensive research programmes involving epidemiological, biological, and medical studies are being initiated around the world. In contrast to ionising radiation, radiofrequency radiation is in general much less understood in the biological and medical community, and it is therefore the purpose of this paper to describe in some detail those technical and physical aspects of modern, wireless digital telephones which can be of relevance for epidemiological, biological, and medical studies.

Non-ionising radiation in the RF (radiofrequency) and microwave region has of course been present for a long time, but has primarily been of significance for military personnel in relation to radar, and in rather specialised industrial situations. The frequency region of interest for mobile phones is from 400 MHz (megahertz) to 2000 MHz (or 2 GHz, gigahertz). From an exposure point of view, this situation has changed dramatically, since now the user of a mobile phone will be carrying a radio transmitter close to the head. This exposure is now rather localised in contrast to previous exposures, which were more ‘whole body’ in character. Due to the requirement for a multi-user system, where a limited spectrum must be utilised by many users at the same time, several new means of exposure are now common with a complicated nature of the time sequence of the signal. Since the biological tissue is exposed to the same complicated signal structure, it is important to understand the variability of the signal, and what aspects of the signal are presently considered to be biologically active.

The understanding of the details of these exposures is motivated by a number of relatively recent studies (Refs 1 and 2 as examples) which seem to show that a high frequency signal amplitude modulated by a low frequency signal gives a different biological response to a pure high frequency wave (a so-called CW or continuous wave) or a high frequency wave with constant power. The responses are similar to the effects obtained by a low frequency signal alone. It can be concluded with some confidence that cells or organisms are sensitive to the time variation of the local power density.

THE BASIC TECHNOLOGY OF MOBILE PHONES

Phase and amplitude modulation of the signal

The key features of phase and amplitude modulation may be understood by considering a simple expression for the instantaneous signal, V(t), as it would appear at the antenna port of the handset:

$$V(t) = a(t) \cos(\omega_c t + \theta(t)) \quad (1)$$

Here a(t) is the amplitude, ω_c is the carrier frequency and $\theta(t)$ is called the phase. All components of the electric and magnetic fields everywhere in space will follow the same general expression apart from an amplitude scaling. A plethora of possibilities exists for modulating the information onto the carrier, but here we shall concentrate on modern digital modulation techniques.

It is important to understand the frequencies involved. The high frequencies carry (thus the name carrier) the information, and these frequencies are important in terms of antenna performance, the spatial distribution of the radio waves, and for spectrum allocation between different regions and services. The actual carrier frequency in Hz is $f_c = \omega_c/2\pi$ and these frequencies are dictated by international agreements for frequency allocation. For present systems these frequencies are around 900 MHz and 1800–1900 MHz. Some first generation analogue systems have carrier frequencies at lower frequencies near 450 MHz. A more correct expression would be to write the carrier frequency as a function of time, since slow frequency hopping is an option in some systems like GSM in order to improve the propagation conditions. If slow frequency hopping is introduced, the carrier frequency f_c jumps between a set of carrier frequencies according to a certain hopping algorithm, changing from one time slot to the next. Fast frequency hopping may be considered a type of modulation connected with instantaneous variations of the phase θ, and will not be considered in this paper.

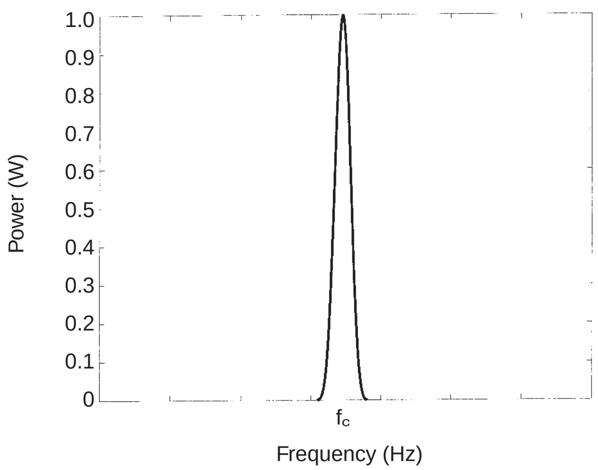

Figure 1. The signal spectrum of a typical mobile phone transmitter. The signal spectrum is distributed in a narrow band around a high frequency carrier.

The purpose of transmitting the radio energy is to transfer information. The information in digital systems are digitised and coded into a sequence of bits which are then phase or frequency modulated. Thus all the information is contained in the phase $\theta(t)$. The instantaneous frequency ω_i is given by the derivative of the phase

$$\omega_i = \frac{\partial\theta}{\partial t} \tag{2}$$

so that the more rapidly the phase is varying, the higher the instantaneous frequency variations around the carrier will be. Thus we can speak of a certain bandwidth of frequencies for a given system, where the bandwidth depends on the bit-rate and the coding. Assuming a random sequence of data we can speak of the signal spectrum, i.e. a function of the distribution of frequencies in the signal. The signal spectrum is maximum at the carrier frequency and decays rapidly outside a width determined by the bandwidth. A sketch of a signal spectrum for a signal is shown in Figure 1.

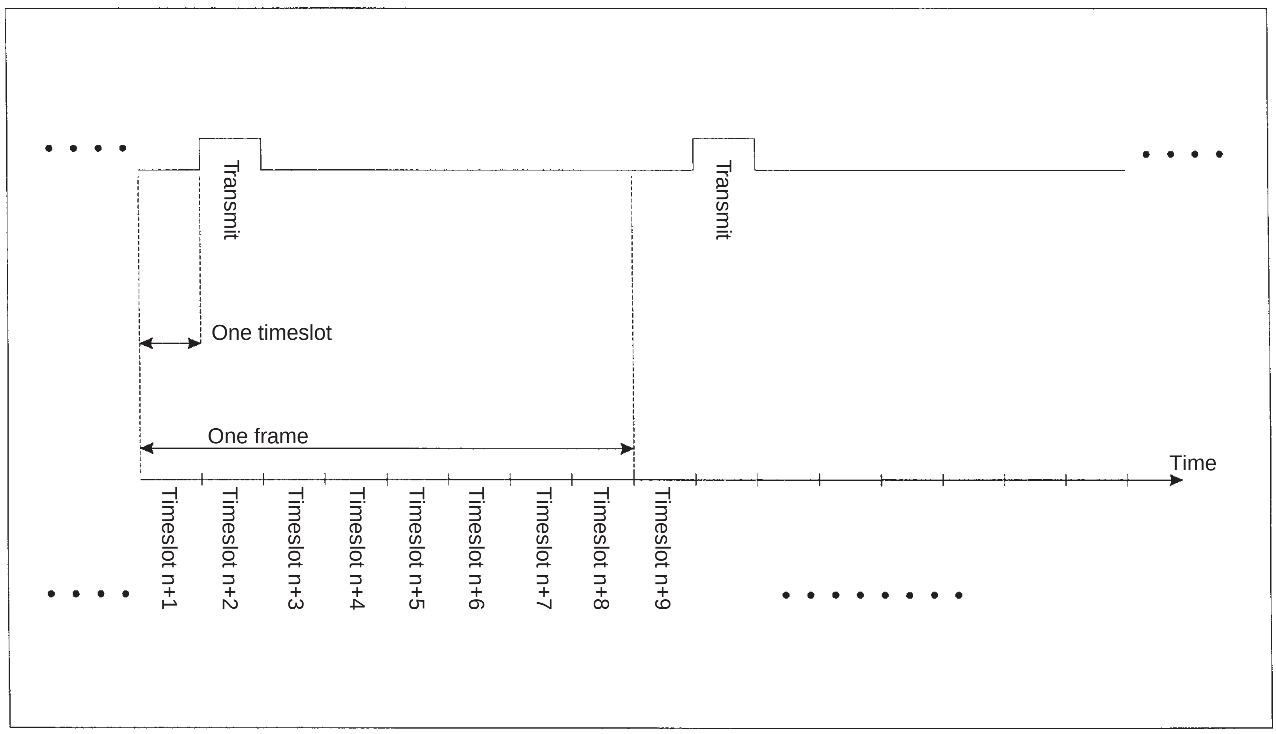

Figure 2. Transmission as a function of time for GSM and DCS-1800 equipment. In this example the handheld equipment is using timeslot number 2 in each frame for transmitting.

Note that there is no power in the low frequency region in the signal spectrum, all the power is concentrated in a narrow frequency band (~0.02%) around the carrier.

The time averaged power (averaged over times much longer than the inverse bandwidth, but shorter than typical times for power variations) can also be studied from Equation 1. The power is related to the square of the signal, i.e.

$$|V(t)|^2 = a^2(t)\cos^2(\omega_c t + \theta(t))$$

$$P(t) \cong \frac{1}{2}a^2(t) \quad (3)$$

where in the second of these equations there is a time average over a period significantly longer than the period of the RF carrier. Thus the power is fluctuating with the square of the amplitude. For technical reasons, signal modulations are often chosen as constant magnitude (also called constant envelope), so if we only looked at the signal itself without any considerations of access methods and power regulations, P(t) would be constant. This is the case for FM (frequency modulated signals for analogue systems) and many digital modulations. In cellular communications for many users, however, the protocols dictate considerable variations in the power, which will be examined next.

Power variations and power spectrum

The power variations depend on two main system parameters: (1) the access scheme, i.e. the way many users share the same spectrum and time, and (2) power regulations. Three access techniques, FDMA, TDMA, and CDMA are outlined below. Power regulations are necessary for capacity considerations and for economy of transmitted power, and will vary from one implemented system to the next. In the following some examples are given.

FDMA

Access

One possibility is FDMA (frequency division multiple access) where each user is assigned a certain carrier frequency and the necessary bandwidth for as long a time as the connection is established. The concept is familiar from ordinary broadcasting. The power is constant as a function of time, so the spectrum of the power has only a value at zero frequency. First generation mobile phones (NMT, AMPS, TACS) use this principle.

Power regulation

Usually only a very slow power regulation is applied, adjusting the output power to what is needed for a sufficient link connection.

TDMA

Access

A second possibility is TDMA (time division multiple access) where a number of users share the same carrier frequency and bandwidth, but at different times. The time allotted momentarily to each user is called a time slot, and each block of time slots is called a frame. A frame in GSM has a length of 4.615 ms (milliseconds), and each time slot has a length of 4.615/8 = 0.58 ms.

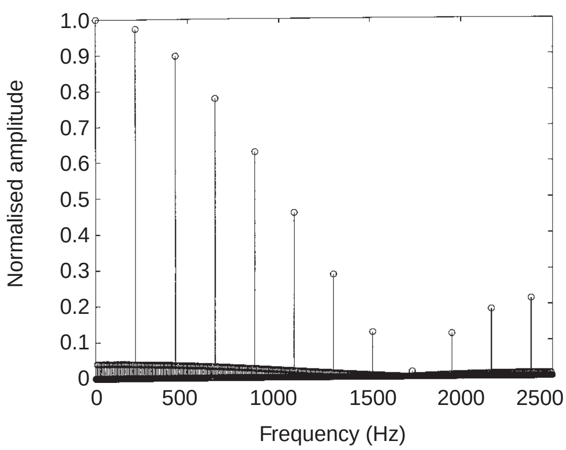

Figure 3. Normalised amplitude spectra of the power. The burst repetition rate of 217 Hz is clearly shown with its harmonics, but also a lower level component of 8 Hz and its harmonics is shown. Note that this spectrum reflects the frequencies involved in the time variation of the power, not the signal spectrum radiated from the antenna (Figure 1). Full-rate GSM spectrum, DTX inactive.

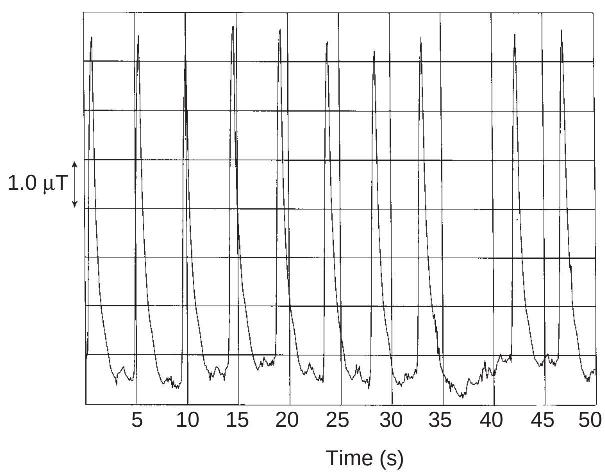

Figure 4. Magnetic fields measured 10 mm from the surface of a handheld GSM phone plotted against time, DTX is not in operation. One burst is missing between peak numbers 8 and 9, corresponding to burst No 26 in a GSM multiframe, which is silent. The absolute Y axis is removed in the plot due to the measured static magnetic field from the earth.

Each user assumes the entire bandwidth for a short time, allows the other users to use the remaining seven time slots, and then returns with full power. When not transmitting, the power is turned to zero, so there is a strong intermittent signal, characterised by 100% amplitude modulations. This is also called a burst mode. The in-between time is partly used for receiving, but in that mode there are no strong fields around the antenna. The timing is shown in Figure 2. It is obvious that for the example shown, GSM, the average power is one-eighth of the peak power. For a GSM handset this would typically be 2 W for the peak power and 250 mW for the average power.

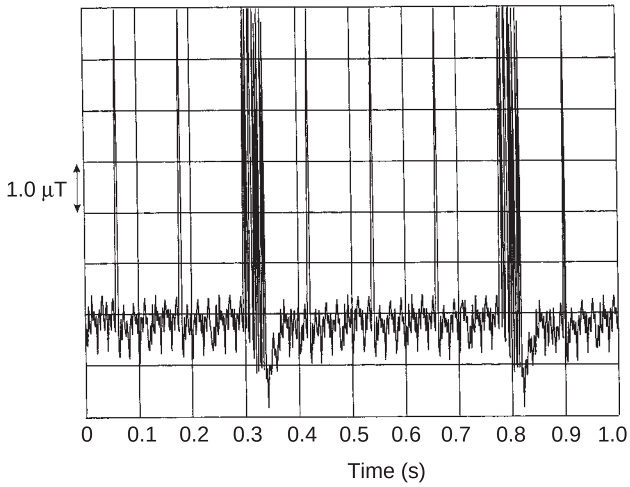

Figure 5. Magnetic fields measured 10 mm from the surface of a handheld GSM phone plotted against time, DTX is in operation. The power saving mode, DTX, employed by GSM phones results in a 2 Hz periodicity. The absolute Y axis is removed in the plot due to the measured static magnetic field from the earth.

Such a periodicity of the power gives rise to a line spectrum of frequencies. The precise spectrum depends on the period, the width of the time slot, and the exact way the signal rises and falls with time. Details may be found elsewhere[(3)], but basically it is a so-called line spectrum with a sinc shape (sin(x)/x), where the frequencies are multiples of $f_0 = 1/(4.615\ \text{ms}) = 217$ Hz. The precise spectrum of the power of a GSM signal is shown in Figure 3.

It is noted that there are frequencies with considerable power in the kilohertz region due to the sharp rises and falls of the power as a function of time. For the GSM system there is a further periodicity due to management subtleties. A so-called multi-frame consists of 26 frames, and for each multi-frame one frame is missing. This creates a periodic variation at a frequency of 8 Hz with an amplitude about 25 times lower than the 217 Hz peak. The average power is thus reduced by a factor of

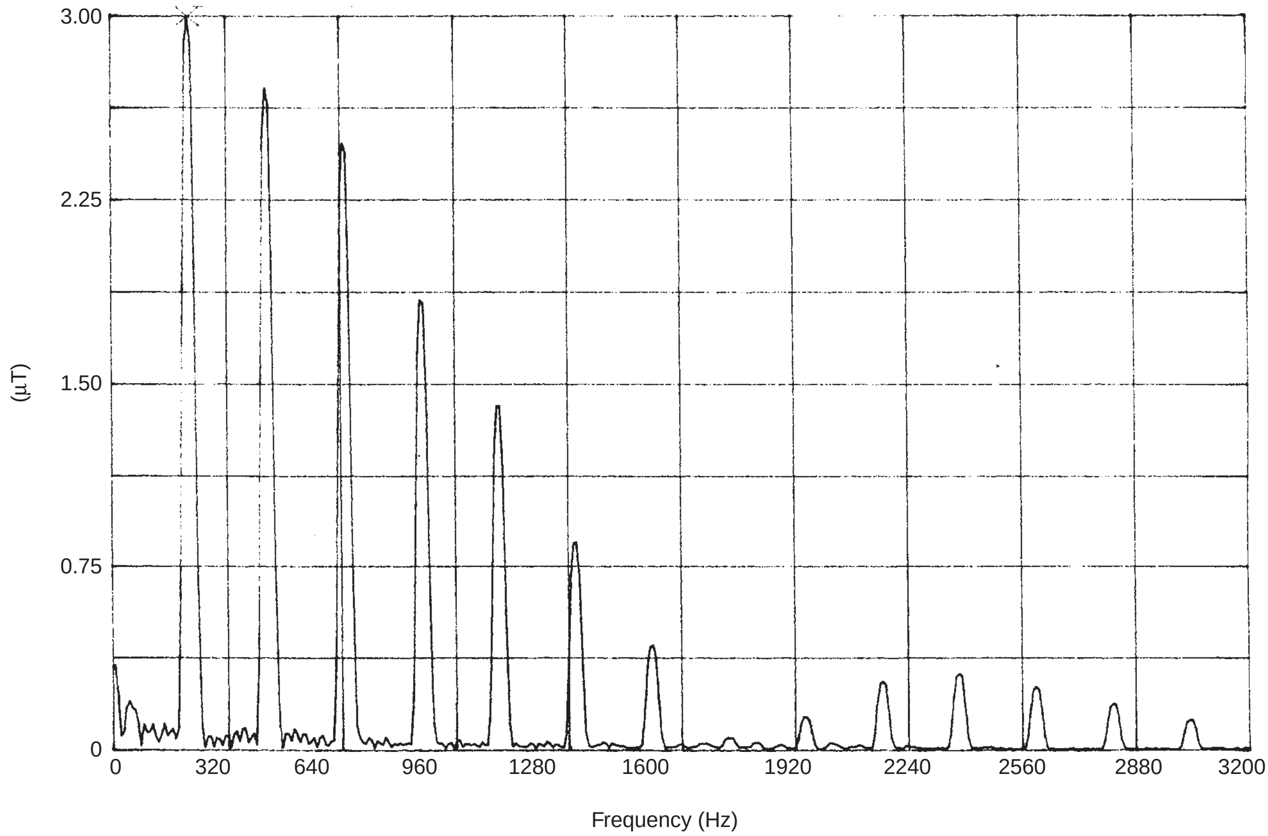

Figure 6. Frequency spectrum of the magnetic fields measured 10 mm from the surface of a handheld GSM phone, DTX is not in operation. The 217 Hz and harmonics of 217 Hz are clearly seen whereas the 8 Hz is unresolved.

25/26, corresponding to an average maximum power of 240 mW for a GSM phone.

A somewhat more random component is introduced for a speech signal, where power is saved in periods of silence, where presumably the other user is speaking. This is called the DTX mode and from a power point of view it is not complete silence. Every fourth multi-frame the noise is sampled and transmitted in eight subsequent bursts. This leads to a frequency spectrum with multiples of 2 Hz and a reduction of the average power by a certain speaker-dependent factor, of the order one half. Some indirect measurements of these power variations will be reported later in the paper.

Power regulation

On top of these periodic or quasi-periodic variations of the power there is a slower variation due to the built-in power control features. In order to reduce the interference from other users each terminal is not permitted to transmit more power than necessary for a link of sufficient quality. If the user is close to a base station it is asked to reduce its transmit power, and this reduction is thus a function of the distance from the base station, but other factors such as local shadowing may also enter the picture. The variations are made in steps of 2 dB (60%), so a terminal transmit power can typically range from a peak power of 2 W down to a peak power of 3 mW (or average powers from 240 mW to 0.36 mW). The averaging times are typically a few seconds, and the variations will be different for a stationary and for a moving user.

CDMA

Access

The CDMA (Code Division Multiple Access) systems operate in a different way by dividing the time and frequencies between different users. There are different systems, but here we will limit the discussion to Direct Sequence (DS-CDMA), which is similar to the IS-95 used primarily in the USA. In principle, each user uses all the bandwidth all the time simultaneously with other users, the distinguishing feature being a coded version of each data bit, such that each user has a different code, which is quasi-random. This means that the signals from other users appear noise-like and the capacity of the system is then limited by the sum of all the interfering signals. The coded data are constant envelope phase-modulated on a carrier as described for TDMA.

As for the other systems, we will concentrate on power variations, and to a first approximation CDMA would appear to be similar to FDMA, since the power is constant with time as far as the basic signalling is concerned. This is, however, too simple an approximation for several reasons.

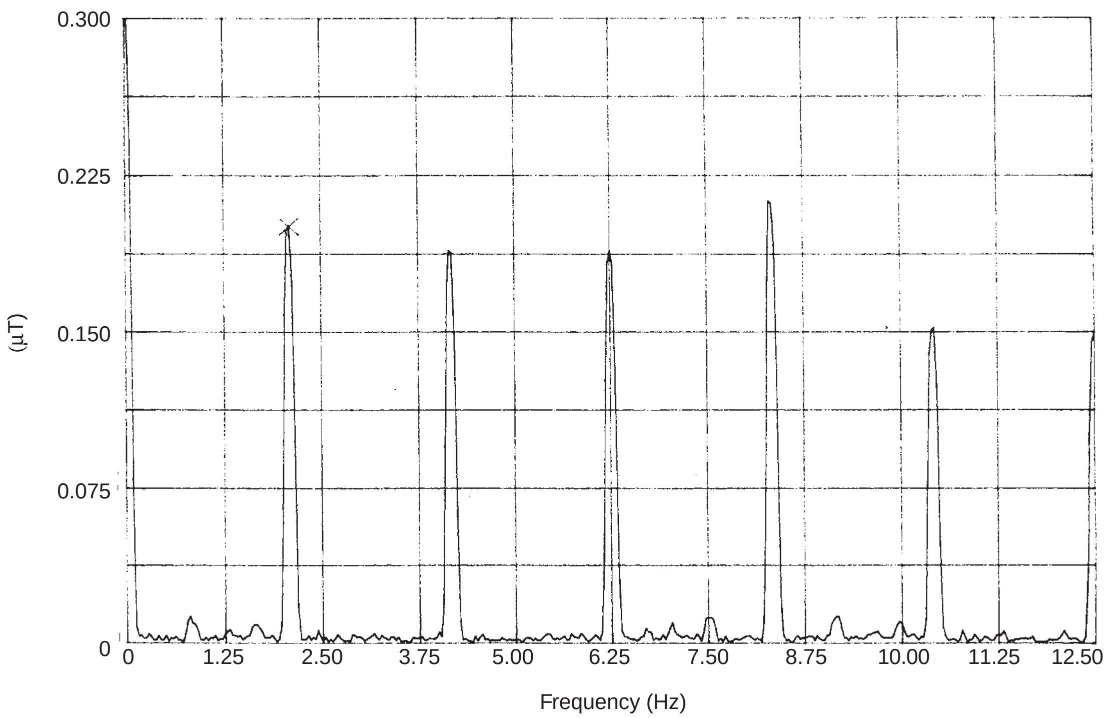

Figure 7. Frequency spectrum of the magnetic fields measured at the same spot on the same phone as shown in Figure 6, but now DTX is in operation. The harmonics of 2 Hz are clearly seen when operating in the power saving mode.

Power regulations

Since each user appears noise-like as an interferer, it is important to diminish the transmission when possible. In CDMA the traffic channel has four different data rates depending on the speech activity. When only the lower rates are transmitted, it is done in burst mode, where the transmitter is intermittently cut off. Thus, it is seen that CDMA power also has the burst pattern nature, but the bursting does not have the regular periodicity of the TDMA case.

It is very important for the proper functioning of a CDMA system that the signals from the mobile stations arrive at the base station at the same power level within a small margin. The mobile unit is adjusting its power level continuously at an 800 Hz rate with changes from 0.5 to 2 dB per step in order to cope with the fast fading (fast power fluctuations due to multi-path propagation). The total power dynamic variations over a short time are of the order 6 dB. The characteristic times are of a random nature since they depend on the speed of mobile user, for a stationary user the fluctuations will be smaller.

Due to the inherent processing gain from the coding the actual radiated power levels are small with maximum power output of the order 200 mW.

EXTERNAL FIELDS

Surrounding the telephone handset is an electromagnetic environment of electric and magnetic fields consisting of a high frequency part, the radiation part necessary for the proper working of the telephone, and a low frequency part due to the low frequency currents in the electronic parts of the handset.

The high frequency fields

As described earlier, all the fields around the antenna will, in each point in space, vary with time the same way as the antenna signal (Equation 1). In the tissue there will thus be a high frequency electromagnetic field (an **E** and an **H**) modulated by the data flow. The local power density proportional to a^2 (Equations 3) will, however, as shown, have low frequency components including a non-zero average value. It has been the tradition to quantify this power density as the SAR value, the specific absorption rate, defined as the time rate of change of the energy in a volume element of a given density:

$$\mathrm{SAR} = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) \tag{4}$$

In electromagnetic terms the time rate of change of energy per volume equals the power density, so

$$\mathrm{SAR} = \frac{\sigma|\mathbf{E}|^2}{\rho} \tag{5}$$

where $|\mathbf{E}|^2$ is the square of the local electric field, σ the electrical conductivity, and ρ the density. Since the square of the electric field is proportional to the power, it is found by comparing with Equation 3, that

$$\mathrm{SAR}(t) \propto a^2(t) \tag{6}$$

This means that all the power variations and power spectra discussed earlier can be transferred directly to the local SAR values in the tissue. The average SAR value is known to have a biological effect and from a physics point of view it has a clear significance as the driving source term for a temperature increase. The possible biological importance of the SAR time fluctuations is still an open question from a biophysics point of view.

The spatial distribution of the SAR in the human head depends on the detailed geometry and tissue composition, the high frequency carrier f_c, and the antenna and handset, so it is a complicated distribution for which only numerical models are available[4]. The complexity derives from the fact that the tissue is in the near-field of the antenna.

The low frequency fields

Very near any electronic device there will always be local stray fields from the charges and the flow of current. For the mobile phone in a bursty mode the current from the battery to the amplifiers follows the same time sequence as the power, and the current gives rise to a magnetic field surrounding the immediate vicinity of the phone.

In the following, some examples of measured ELF magnetic fields are given for two TDMA systems, namely GSM and DECT (Digital Enhanced Cordless Telecommunication). The magnetic field measured near the handheld stems from the current drawn from the battery packed to supply the power amplifier and possible other essential components which are switched on and off according to the TDMA scheme. The amount of current drawn depends on the transmitted power which is standardised for each system, and the battery voltage. For this reason the voltages of the battery packed in the handheld are of great interest. Typical handhelds today are using battery packages with a voltage of 6 V, but packages with 3.6 V are now available. A handheld operating in a bursty TDMA system where the transmitter is turned on and off according to the TDMA scheme, the current drawn from the battery will also be of a burst nature and quite large. For example, a typical 2 W peak power GSM phone having an efficiency of, say, 45% will draw a burst current in the order of 0.75 A (and at 3.6 V the current will be nearly twice that).

It is important to note that the ELF fields stem from the current drawn from the battery and not from the antenna signal which transmits the RF signal as described in the previous section.

Measurements

To measure the ELF magnetic fields surrounding the handheld phone a small magnetic field probe is used to scan the surface of the phone to obtain the maximum value of magnetic fields. The probe is a Bartington Fluxgate probe capable of measuring over a bandwidth starting at static magnetic fields to magnetic fields varying at 2.3 kHz (–6 dB). Measuring on a GSM phone which has RF power regulation as described in a previous section it is necessary to know which power level the phone is using. For DECT phones where no power control exist the measuring set-up is simpler.

GSM

To ensure that the GSM phones were transmitting in the highest power level the external antenna connector was used with a variable attenuator in series with the external antenna. This arrangement was used to ensure high enough propagation loss to force the phone to transmit with the highest power level while retaining sufficient quality of the connection with the base station. The external antenna was mounted on top of the building containing the laboratory in order not to interfere with the ELF measurements.

The measured signals are very similar to the TDMA scheme for GSM and Figures 4 and 5 show examples of the measured signals in the time domain without and with DTX in operation, respectively. In Figure 4 where DTX is inactive the burst repetition time is 4.615 ms as expected whereas the shape of the timeslot is somewhat different from the 1/8 of the frame time due to power consumed by other essential components in the phone and the cut-off frequency of the probe. Furthermore, during one of the frames shown no time slot is sent, this is timeslot number 26 in all multiframes as explained previously. The absolute ordinate axis is removed due to the earth's static magnetic fields.

In Figure 5, DTX is in operation and now the time scale is much larger than in the previous figure. The time between the widely spaced timeslots constitutes a multiframe (26 frames = 0.12 s) and these timeslots are carrying system related information. The closely spaced timeslots also shown are carrying the sampled background noise and are sent in eight consecutive timeslots every fourth multiframe (0.48 s).

Figures 6 and 7 show the measured spectra without and with DTX in operation, respectively and the similarity with the line spectrum for the TDMA scheme in GSM is strong. The measured spectra are not identical

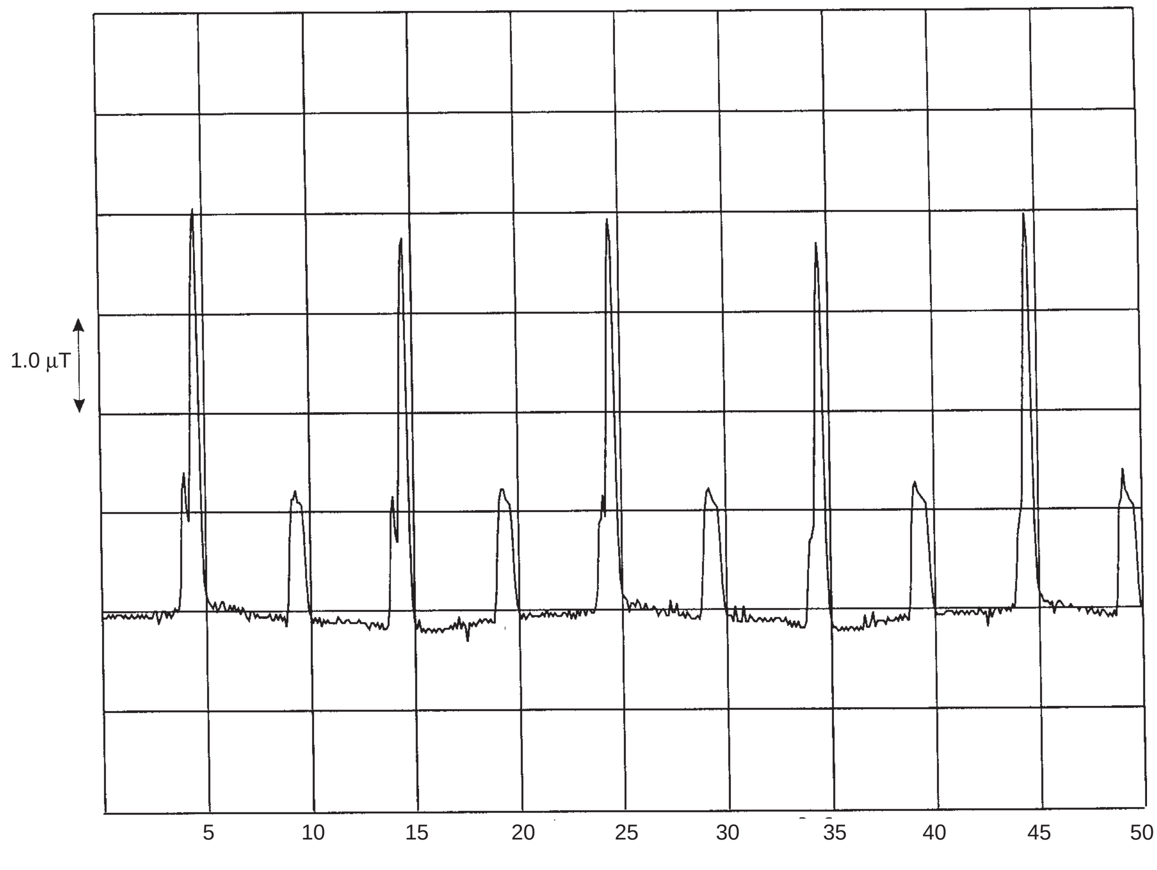

Figure 8. Magnetic fields in the time domain near a DECT phone in the time domain. The absolute Y axis is removed in the plot due to the measured static magnetic field from the earth.

to the TDMA scheme because the current drawn from the battery depends also on the hardware, e.g. if large capacitors were used at the supply in the transmitter or if the current drawn for other blocks than the transmitter are significant. When DTX (the power saving mode) is in operation an additional repetition rate component of 2 Hz arises, see Figures 5 and 7.

The magnitude of the highest single frequency component, 217 Hz, on four different commercial available GSM handheld phones was 0.2–0.41 μT on the front of the phones and 0.3–3.0 μT on the back of the phones. The highest value was measured on the back of one of the phones and this measurement is also shown in Figure 6. The measurements shown in Figure 7 are also taken at the same location on the same phone but when the DTX is in operation.

Only one GSM phone was measured in the time domain and the results as a function of time are shown in Figures 4 and 5. This phone has a 0.41 μT component at 217 Hz on the front which equals a 6 μT peak magnetic field in the time domain. This indicates that at the back of the phone having a field component of 3.0 μT at 217 Hz the peak magnetic field could be some 40 μT.

DECT

For measuring ELF magnetic fields on the DECT phones the set-up was simplified because no RF power control is implemented in the DECT standard. The base station was moved to an adjacent room and a call was established from the handheld when the measurements were conducted.

Figures 8 and 9 show the measured magnetic field of a DECT handheld in the time and frequency domains, respectively. The repetition rate in DECT is 100 Hz but as can be seen in Figure 8, peak currents are drawn both for the transmit operation (the high narrow peaks) as well as for the receive operation. The reason is that in order to save battery power the handheld is turned off between receiving and transmitting.

Two commercially available DECT phones were measured and the results of the highest single frequency components, 200 Hz, were 0.14 μT and 0.28 μT on the front and 0.14 μT and 0.50 μT on the back of the phones.

The field values for the DECT phones are not much different from the values measured for the GSM phones which is somewhat surprising since the GSM phones are transmitting with much higher power than the DECT phones. There are two reasons for that, one is the battery voltage is 3.6 V for the DECT phones whereas it is 6 V for the GSM phones, resulting in a higher current for a given output power. The other reason is that only current variations as a function of time result in varying magnetic fields and the DECT phones are turned off between transmitting and receiving whereas in GSM phones only certain blocks are turned off due to the stronger restrictions on the modulation.

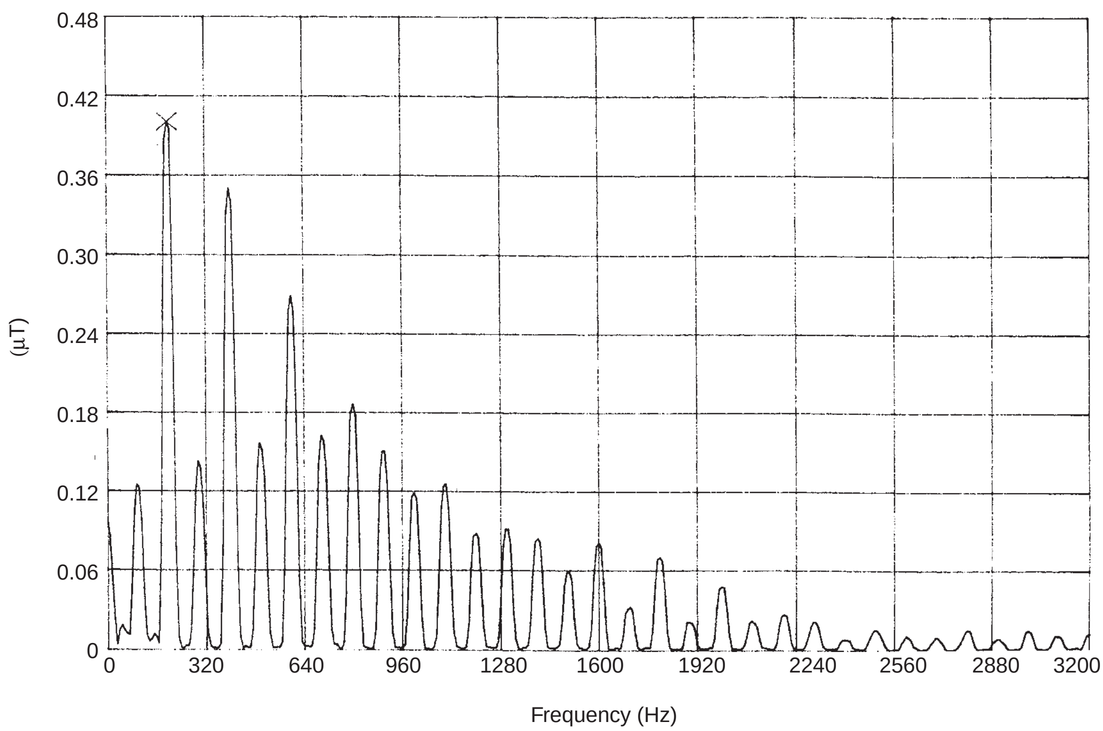

Figure 9. Magnetic fields in the frequency domain near a DECT phone. Note that the strongest single component is not the one arising from the frame repetition time (10 ms) but twice this value, namely 200 Hz. The reason is that a DECT phone turns off the power between transmit and reception as can be seen in Figure 8.

CONCLUSION

Biological effects of the fields around mobile phones are assumed to be dependent on phenomena with a time variation at low frequencies, by which we mean of the order a few hundred Hz down to DC, zero frequency. The reason for this assumption is that no athermal biological experiments are known in the frequency range around 1 and 2 GHz, where the present day phones are working. If the millimetre range is considered with frequencies from 20 to 60 GHz the situation could be different, but this is not included in the present paper. The two low frequency phenomena considered are variations with time of the local power density (proportional to the Specific Absorption Rate, SAR) and the direct effects of low frequency magnetic fields.

The average SAR, averaged over time, is the only parameter accepted today by the regulating and standards bodies, but a number of experiments involving the time varying SARs are under way at many institutions. From the point of view of protection, some systems are better than others in the sense that the power variation with time is smaller or less coherent. The radiations themselves cannot be avoided, but there are possibilities of antenna design in which the shielding from the antenna case is utilised and the radiation into the head is greatly reduced.

The other low frequency magnetic fields are commensurate with fields emanating from many household devices, although the spectrum is different. Since the main contributions are from the battery currents there are ways of arranging the wiring to minimise the external fields, so this should not be a major problem.

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