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THE SIGNIFICANCY ANALYSIS OF THE OBJECTS HEATING IN THE ELECTROMAGNETIC FIELD RADIATION OF MOBILE DEVICES FOR CELLULAR COMMUNICATION SYSTEM

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In our study we consider sets of factors that determine the objects heating in RF radiation of cellular mobile devices. In reality, the range of emitting power can vary widely and is depended on many discussed factors. There are factors that determine the level of absorbed power as a function of the physical characteristics of objects in SAR estimations. The third group of factors determines the heating of the object as a result of radiation energy absorption and heat energy return into the environment. The experiments have showed significant (measurable) effects of heating of the objects in the field of radiation of mobile devices when they are in a call (the traffic is transmitted). The smooth statistical analysis of experimental data allowed us to estimate some of the parameters that are difficult to find on the basis of theoretical calculations. Analytical expressions describing the process of change in temperature of objects are also given.

Keywords: RF power, mobile communications, SAR, regression analysis, R environment

1. Introduction

The considerable popularity of the cellular communication systems increases and it is estimated by World Health Organization (WHO) [1] that at the end of 2009 about 4.6 billion users were registered. The number of users of mobile devices increases rapidly and in 2011 about 6.8 billons cellular phone subscriptions has been registered [2]. The statistical data available from cellular systems providers indicate an average airtime of about 30 min/d and an average call length of about 3 min/user [3]. These figures are typical for voice calls but the data transmission calls become more and more popular and for them the call length may be much greater. Extensive cell phone use is known to present the highest radio frequency (RF) exposure to the general public and objects that are in close proximity to transmitting device. Research efforts starting in the early 1980s to assess the health effects from cell phone radiation have focused on the significant absorption of radiation by those parts of the human brain that are close located to the antennae of the device [4]. Investigations involve the continued relevance issues of different types of electromagnetic radiation influence factors on environment for mobile devices. The short and long-term effects on human health are being studied.

In general, the effects of non-ionizing radiation have been divided into thermal and no thermal. The predominant scientific opinion sees the conversion of absorbed radiation into Joule heat as the dominant effect with possible biological consequences, accurate measurements of its dynamics magnitude inside the living human body are lacking and very smooth methods to have thermal dynamics inside brain tissue under exposure to power and irradiation time-varying RF fields are under consideration [5].

In our discussion we consider the thermal dynamics model for small objects that may be characterized by the homogeneous physical properties and that are under irradiation of time-averaged RF of mobile devices in a call. Energy emitted by mobile devices is in principle partially absorbed by objects in the field of radiation, what leads to an increase in their internal thermal energy, and in some circumstances to increase in their temperature. The rate for temperature changes are in our model characteristics of the entire object (is spatial averaged). In the real world such an increase in temperature of objects can also be considered in many cases as highly undesirable phenomenon, which could have a negative impact in chemical reactions, accuracy of physical measurements, disruption of hydrogen bonds in the protein substance (just what is happening when the egg is being cooked), etc. The prediction and estimation in object's temperature changes for the real worldwide of cellular mobile devices users is of interest.

2. Factors of Emitted RF Power

Cell phone radiation exposure generally depends on emitted RF power. The maximum RF power emitted from handsets varies as mobile technology has evolved through generations (1G, 2G, 3G, etc.)

using different multiple access technology and communication protocols. Cell phones can emit peak power in conformity with their power class. For GSM 900/1800 technology 5 power classes for user devices are defined (Table 1), for UMTS (Universal Mobile Telecommunication Systems),- 4 power classes with maximum power 2W/0.5W/0.25W/0.125W (for FDD option) and 1W/0.25W/0.125W/0.1W (for TDD option). WHO consider that for handsets available today the range of peak power is 0.1-2W [1].

Table 1. The peak (maximum)P_{max} and time-averaged P_{avr} RF power for cellular devices operating in GSM 900/1800 system

GSM PowerClass	GSM 900			GSM 1800		
	Power level	P_{max}	P_{avr}	Power level	P_{max}	P_{avr}
1				PL0	1W	< 0.125W
2	PL2	8W	< 1W	PL3	0.25W	< 0.03W
3	PL3	5W	< 0.625W	PL29	4W	< 0.5W
4	PL4	2W	< 0.25W			
5	PL5	0.8W	< 0.1W			

Through multiple access techniques such as time division multiplexing (TDMA), mean output power P_{avr} is much lower. For example, global system for mobile (GSM) cell phones at frequencies of 1800 and 900 MHz with maximum output powers corresponding to their class operate at mean powers with coefficient 0.125 (see Table 1) by enabling eight users to share one frequency channel simultaneously. The RF output power in this case can discretely reach the peak power P_{max} in short bursts (0.577 ms) during a call. A similar reduction factor is also characteristic of technologies HSCSD (High Speed Circuit Switched Data), GPRS (General Packet Radio Service), EDGE (Enhanced Data rates in GSM Environment), and the number of time slots used in data transmission can be changed during a call, so the reduction factor varies:

HSCSD - 0.125 ÷ 0.5
GPRS - 0.125 ÷ 1
EDGE - 0.125 ÷ 1

Discontinuous power control (for GSM with frequency about 1 Hz and for UMTS about 1.5 KHz) is the second factor that reduces averaged power (respectively, maximum power times TDMA reduction factor, it is shown in Table 1) but such reduction depends on concrete conditions in the cell during a call.

Although, third and fourth generation (3G technologies UMTS, HSPA and 4G LTE) cell phones have lower mean output powers (about 0.1mW in [6] research), future cell phones may generate even more emissions to enable signalling at higher data rates [7].

Thus, it is important to investigate a wide range of power levels to include the past, present, and future power emission scenarios. Accurate investigations [6, 8] have given the next P_{avr} values for different cellular technologies:

AMPS - 171mW
GSM - 26mW
TDMA (IS-136) - 66mW
CDMA (IS-95) - 0.9mW
UMTS - 0.07mW

However, there is always a non-zero probability for mobile device to work at a power more near to P_{max} and take into account this fact we will recommend some other way for the estimations of the absorption energy levels.

3. Factors of Power Absorption

It was possible to define on international level the acceptable degree of energy absorption per unit time per unit weight of a body (SAR - Specific Absorption Rate). Current applied methods to characterize SARs compromise measurement accuracy by emulating real cell phone use. Industrial standards for SAR assessment suggest scans of the RF fields with electrical field probes in head phantoms

[9], whereas computer-based simulations predict RF field distributions in the head [10]. The Federal Communications Commission (FCC) in the United States has set a SAR limit of 1.6 W/kg averaged over 1 g of tissue for partial-body exposure, whereas the Council of the European Union allows a limit of 2.0 W/kg averaged over 10 g of tissue [11, 12]. For this activity a process for the publication the corresponding parameters SAR for each commercially available mobile device is defined.

By definition:

$$SAR = \frac{\sigma |E|^2}{\rho}, \tag{1}$$

where σ is the electrical conductivity [S/m]; ρ is the density [kg/m^3]; E is the electric field [V/m]. In industrial SAR estimations for mobile devices it is believed that physical parameters of RF energy absorbing substance need to be close to human body tissue and E needs to be measured inside the substance of irradiated object. Often water-triton-salt (WTS) gel emulates brain tissue with a target permittivity (ε_r) of 44, electrical conductivity (σ) of 1.4 S/m at 1.9 GHz RF frequency [13], and density (ρ) of 1026 kg/m^3 and possesses semi-liquid properties below the temperature of 23 °C. These characteristics are very similar to the characteristics of salted water.

So, the power of RF energy that is received by object P_{ext} (for the object it is an external energy) and after that is converted into its Joule heat is estimated as:

$$P_{ext} \approx SAR \cdot m, \tag{2}$$

where m is mass [kg] of the object. The SAR data are available for mobiles of different technologies (0.7 - 0.9 W/kg for GSM900/1800 and 0.2 - 0.5 W/kg for UMTS), but m needs to be small enough ($P_{ext}<P_{avr}$ in the physical sense of the process, see Table 1). If physical parameters of object's substance differ from figures for WTS, SAR may be recalculated using relation (1) but to a certain extent (the model of SAR does not apply to metal objects).

3. The Model of Heating

The next group of factors determines the heating of the object as a result of radiation energy absorption and heat energy return into the environment. It was assumed in our discussion that the conditions are near room conditions, and the temperature is on the order of 293^{0}K. For the object's temperature rise can be approximated by heat equation:

$$dT = \frac{P_{ext} - \varepsilon\sigma_{S-B} S(T^4 - T_{env}^4) - hS(T - T_{env})}{C_{obj}} dt, \tag{3}$$

where T is temperature of the object [^{0}K]; T_{env} is temperature of the environment [^{0}K]; ε is emissivity (in our case for gray body); $\sigma_{S\text{-}B}$ Stefan–Boltzmann constant equals $5.6704\cdot10^{-8}$ [W/(m$^2\cdot^0$K^4)]; S is object's surface area [m^2]; h is heat transfer coefficient [W/(m$^2\cdot^0$K)] in Newton's low; C_{obj} is specific heat of the object [J/^{0}K] equals $c_s\cdot m$ (c_s - specific heat of object's substance [J/(kg$\cdot^0$K)]; t is a time [s].

In the heating model equation (3) we suppose that the object will receive heat by absorption of external electromagnetic radiation in its volume (the term $P_{ext}\cdot dt$) and will lose heat through its surface. The heat losses are determined by two physical processes, namely, thermal radiation (~ΔT^4) and convection in the external environment (~ΔT).

As you can see in (3) there is no term comprising $\nabla^2 T$ like in Pennes' bio heat equation [14], it just means the spatial averaging for the temperature of a small object, it is also true that for that objects h < χ/l, where χ - thermal conductivity [W/(m$\cdot^0$K)]; l - linear dimension of the object [m]. In bio equation [14] the convection is taken into account through volumetric perfusion rate of blood, for us it is rather convection in air environment. In bio equation [14] the thermal radiation losses are not taken into account due to the nature of objects under consideration, but we will consider this type of loss.

Separating the variables in (3) for integration and assuming that $(\Delta T/T_{env})^2 \ll 1$ we receive:

$$\frac{d\Delta T}{a\Delta T^2 + b\Delta T + c} = -dt, \text{ where } a = \frac{6\varepsilon\sigma_{S-B} S T_{env}^2}{C_{obj}}, b = \frac{4\varepsilon\sigma_{S-B} S T_{env}^3 + hS}{C_{obj}}, c = -\frac{P_{ext}}{C_{obj}} \tag{4}$$

The integration of (4) gives:

$$\frac{2}{\sqrt{b^2-4ac}} arth \frac{2a(T-T_{env})+b}{\sqrt{b^2-4ac}} \Big|_{T_0}^{T} = t \text{, when} (2a(T-T_{env}))^2 < b^2-4ac \text{ and}$$

$$\frac{2}{\sqrt{b^2-4ac}} arcth \frac{2a(T-T_{env})+b}{\sqrt{b^2-4ac}} \Big|_{T_0}^{T} = t \text{,when} (2a(T-T_{env}))^2 > b^2-4ac, \tag{5}$$

where T_0 is the object's temperature at the moment t=0.
If in the initial moment of time the object was in a thermal equilibrium with the environment, it means that $T_0=T_{env,}$ from (5) we receive dependence ΔT(t) as:

$$\Delta T = \frac{2c(1-e^{(\sqrt{b^2-4ac})t})}{\sqrt{b^2-4ac}-b+(\sqrt{b^2-4ac}+b)e^{(\sqrt{b^2-4ac})t}} \tag{6}$$

In (6) ΔT=0 when t=0 and there is a maximum of temperature $\Delta T_{max}$when t→∞:

$$\Delta T_{max} = \frac{-2c}{\sqrt{b^2-4ac}+b} = \frac{-b+\sqrt{b^2-4ac}}{2a} \tag{7}$$

Moreover, there is a typical time for temperature increase of the order of $t_{typ} = \dfrac{1}{\sqrt{b^2-4ac}}$; it is so because ΔT can be expressed by ΔT_{max}:

$$\Delta T = \frac{\Delta T_{max}(e^{(\sqrt{b^2-4ac})t}-1)}{\dfrac{\Delta T_{max}}{\Delta T_{max}+\dfrac{b}{a}}+e^{(\sqrt{b^2-4ac})t}} \approx \Delta T_{max}(1-e^{-(\sqrt{b^2-4ac})t}), \tag{8}$$

when ΔT changes "significantly" (about 60% of achievable maximum). Due to (7), (8) and (4) for the object with physical parameters like a "chicken egg" for SAR≈1.7 W/kg and T_{env}≈19⁰C our estimation will give: ΔT_{max}≈ 0.8⁰, t_{typ} ≈ 2700 s. So, for such objects the heating effect exists but is small enough.

4. The Experiment of Heating

We have conducted several experiments to obtain more accurate values of the physical parameters included in (4). In one of them salted water in PVC glass was heated in the RF fields of two mobile phones that were in a call in GSM900/1800 network. Characteristic parameters of the object were as follows:

Table 2. Characteristics of the object in the experiment of heating

l [m]	S [m^2]	V [m^3]	m [kg]	C_{obj} [J/^{0}K]	ρ [kg/m^3]	χ [W/(m·^{0}K]	σ [S/m]
0,018	5,77E-03	3,37E-05	0,034	140,54	998,23	0,6	3

T_{env} was 292.5^{0}K. The total value of SAR for two devices was 0.86+0.81=1.67 W/kg. Measuring temperature inside the object over time we have received the next data set:

Table 3. Changes in temperature with the time of the experiment

t [s]	0	600	1200	1800	2400	3000	3600	4200	4800	5400
ΔT[^{0}C]	0	0	0.1	0.1	0.3	0.3	0.2	0.2	0.3	0.3

5. The Regression Analysis

Further processing of the results of the experiment was performed using a nonlinear regression analysis in R environment [15]. The model corresponding to experimental data is (6) in our case. Using (4) definitions, for convenience, we have introduced the following notation:

$a = \frac{6\varepsilon\sigma_{S-B} S T_{env}^2}{C_{obj}} = A\theta_1$, where just $\theta_1 = \varepsilon$

$b = \frac{4\varepsilon\sigma_{S-B} S T_{env}^3 + hS}{C_{obj}} = B_1\theta_1 + B_2\theta_2$, where just $\theta_2 = h$

$c = -\frac{P_{ext}}{C_{obj}} = -C\theta_3 = -\frac{SAR * m}{C_{obj}}\theta_3$, where θ_3- dimensionless coefficient takes into account the deviation of the actual power absorbed from SAR (9)

The real complexity of the nonlinear regression analysis arise from the fact that in our case the input parameters have a strict physical sense, can be changed only in a specific range, and have preferable initial values. For our regression model the parameters are collected in Table 4.

Table 4. The model parameters in correspondence with (9) and characteristics in Table 2

Parameters of nonlinear regression model				Initial estimations		
A	B_1	B_2	C	θ_1	θ_2	θ_3
1,19E-06	2,33E-04	4,11E-05	3,99E-04	1	1,49	1

On the next printout of R console you can see the main facilities of R environment that we are using for the "best" estimations (on the residual sum of sequence base minimizing) when the estimated parameters need to save the physical meaning:

Table 5. Search of parameters for a choice of the best smoothing in environment R with console printout comments

<table>
<tr><th>Console printout</th><th>Comments</th></tr>
<tr><td><pre>> windows()
> ObservH1 <- data.frame(y<-
c(0,0,0.1,0.1,0.3,0.3,0.2,0.2,0.3,0.3),x<-
c(0,600,1200,1800,2400,3000,3600,4200,4800,5400))
> ModelH1 <- function (x,teta1,teta2,teta3)
+ {
+   A=1.19*10^(-6)
+   B1=2.33*10^(-4)
+   B2=4.11*10^(-5)
+   C=3.99*10^(-4)
+   a=A*teta1
+   b=B1*teta1+B2*teta2
+   c=-C*teta3
+   z=(b^2-4*a*c)^0.5
+   2*c*(1-exp(z*x))/(z-b+(z+b)*exp(z*x))
+ }</pre></td><td>Data frame definition. In corresponds with the experiment data in Table 3.

Data model definition in accordance with equation (6), (9) and parameters in Table 4.</td></tr>
<tr><td><pre>> plot(y ~ x, lwd=5)
> curve(ModelH1(x, teta1= 1, teta2 = 1.49, teta3=1),col="green",
add = TRUE)</pre></td><td>The plot of defined model construction for initial estimations of parameters in Table 4.</td></tr>
<tr><td><pre>> grid.Obs <- expand.grid(list(teta1=seq(0.1, 1,
by=0.1),teta2 =seq(0, 10, by= 0.1), teta3=seq(0,1,by=
0.01)))</pre></td><td>Search on a grid in R environment is done as follows</td></tr>
</table>

Console printout	**Comments**
> > ObservH1.m2a <- nls2(y ~ ModelH1(x,teta1, teta2,teta3), data = ObservH1,start = grid.Obs, algorithm = "brute-force") > > ObservH1.m2a Nonlinear regression model model: y ~ ModelH1(x, teta1, teta2, teta3) data: ObservH1 teta1 teta2 teta3 1.00 2.20 0.29 residual sum-of-squares: 0.03183 Number of iterations to convergence: 102010 Achieved convergence tolerance: NA	Nonlinear regression function nls2 is used for on grid searching Results of the done analysis allow to receive the parameters minimizing RSS on the grid
> curve(ModelH1(x, teta1 = 1, teta2 =2.2, teta3 =0.29),col="blue",add = TRUE)	The plot of defined model construction for parameters calculated on previous step
> ObservH1a.m2 <- nls(y ~ ModelH1(x,teta1,teta2,teta3), + data=ObservH1, start = list(teta1=1,teta2=2.2, teta3=0.29)) > ObservH1a.m2 Nonlinear regression model model: y ~ ModelH1(x, teta1, teta2, teta3) data: ObservH1 teta1 teta2 teta3 9.075e+03 -5.151e+04 1.472e-02 residual sum-of-squares: 0.02195 Number of iterations to convergence: 20 Achieved convergence tolerance: 8.028e-06	Once more choice of parameters is carried out within the limits of known iterative standard function of a package nls and results in the following: The RSS is less than in previous case, but parameters are out of physical sense region
> curve(ModelH1(x, teta1 = 9.075*10^3, teta2 = -5.151*10^4, teta3 = 1.472*10^(-2)),col="brown", add = TRUE)	The plot of defined model construction for parameters calculated on previous step

On Figure 1 the experimental data set and nonlinear analysies curvs are visualized.

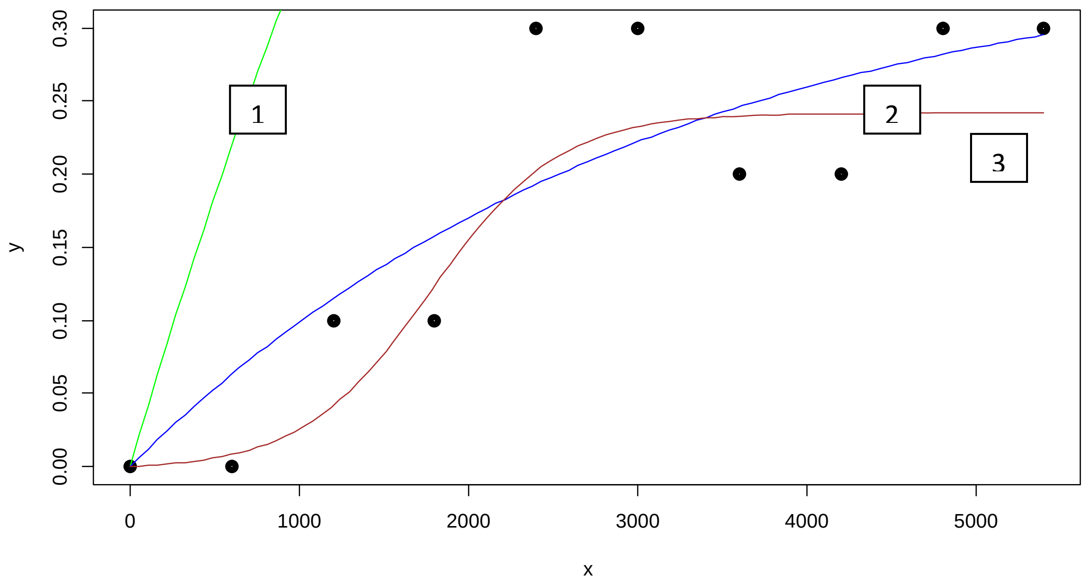

Figure 1. On the axis Y – ΔT [^{0}], on the axis X – t [s]; Experiment data set of object's heating (dots); Regression curve corresponding to initial value (Table 4) of θ parameters – 1(green); Regression curve θ_1=1, θ_2=2.2, θ_3=0.29 (parameters in the range "of physical sense") – 2(blue); Regression curve corresponding to the best RSS (parameters are out "of physical sense") – 3(brown)

As regression analysis gives us a good estimation of θ parameters we can also estimate the maximum temperature of heating for experimental object. From (7) and with definitions (9) we find:

$$\Delta T_{max} \approx \frac{SAR * m\theta_3}{S(4\sigma_{S-B} T_{env}^3 \theta_1 + \theta_2)} \,. \tag{10}$$

For the previously mentioned parameters of object, environment and mobiles, and with θ_1=1, θ_2=2.2, θ_3=0.29, (10) gives us that $\Delta T_{max} \approx 0.36^0$. So in our experiment, we have almost reached the limit temperature.

6. Conclusions

As a conclusion we can say that we have an applicable model for estimations of heating the objects as a process of RF energy absorption and heat energy return into the environment. The parameters of the model are characterized by the fact that ε (emissivity) is close to 1 and h (heat transfer coefficient, rather hard parameter for estimation) is of the order of several units (2.2 [W/(m^2•^{0}K)] is a good estimation in many cases). As for absorbed energy, it can be estimated using data of SAR for mobile devices but under real cellular networks conditions only about 30% SAR energy is absorbed. Heating effect is rather small but can be observed and could have a negative impact for the objects of different types in real world.

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