Impact analysis of mobile phone electromagnetic radiations on human electroencephalogram

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Abstract. The experimental study of electromagnetic interference of mobile phone radiations on brain waves is a contemporary research area and the ever-increasing use of mobile phones make it more imperative to explore the problem area in detail. Electromagnetic signal from mobile phones operating in Global System for Mobile (GSM) and wide band code division multiple access (WCDMA), has been considered in this paper and their interference impacts have been analyzed on the human electroencephalogram (EEG). The impact on brain waves i.e., delta, theta, alpha, beta and gamma waves are analyzed in five modes namely ideal mode i.e., when mobile phone is not in use, transmission mode and the receiving modes of second generation (2G) and third generation (3G) networks. The data has been acquired from 75 young and healthy students of a post graduate institute while the students were making their routine calls. The acquired EEG signal is analyzed using various parameters viz.; Approximate Entropy (ApEn), Largest Lyapunov Exponent (LLE), Hurst Exponent (HE), Correlation dimension (CD) and the power of the brain waves have also been analyzed. It has been found that due to mobile phone usage, there is variation in the nonlinear parameters and increase in the power of the alpha brain waves at T5O1 during 3GRx and decrease in alpha power at the P4O2 channel in all modes. It has been observed that the change at the right temporal region is more, the side to which mobile phone was held. The Statistical analysis has also been done using SPSS software which shows significant variations at some of the channels in different modes.

Keywords. Approximate entropy; correlation dimension; electromagnetic radiations; Hurst exponent; largest lyapunov exponent.

1. Introduction

The increasing demands for wireless equipments utilizing RF spectrum especially mobile phones have opened up a basis to explore the impact on human beings mainly on the brain. Brain is a vital part of our body and is in close proximity to the radiations from the mobile phones. Radio Frequency (RF) signal is an electromagnetic radiation that has the ability to affect the human body due to its composition of water electrolytes and ions. The exposure due to radiations from towers or other gadgets is on whole body whereas that from the mobile phone handset is a kind of local exposure [1] and is very near to our brain, thus, is a matter of concern. Thermal radiations from the mobile phone is quantified by the specific absorption rate (SAR) value which causes heating of the tissues that increases with the duration of the mobile usage [2]. In view of public and governmental concern, World Health

Organization established the International Electromagnetic Fields (EMF) in 1996 to assess the adverse effects of these fields. In 2016, WHO also conducted a formal risk assessment study for radiofrequency fields exposures [3]. But in this paper, specifically GSM and WCDMA have been considered which have more users. GSM network is a TDMA based network and operates in the range of 900–1800 MHz. WCDMA operates in the frequency range of 2100–2170 MHz [4]. The possibility of their biological, physiological and psychological effects on the human body has led to the analysis of their effect in detail. Literatures have also pointed to an effect on the EEG by low level RF radiations [5]. The EEG signal beta wave is sensitive to these microwave radiations and depends on its frequency [6].

Electroencephalogram depicts the electrical potential on the scalp of the head acquired using the electrodes. The amplitude of the human EEG is 10–15 μ V and the frequency is below 30 Hz [7]. The International 10–20 system is used for the placement of the electrodes. 10 and 20

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Figure 1. Subject in normal mode.

Figure 2. Subject using mobile phone.

usually denotes the distance between the electrodes and 10% or 20% of the front to back and right to left, placed over the scalp [8]. EEG is due to the neural activation inside the brain that controls the functioning of the whole body system. EEG consists of five brain waves viz; delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta1 (12–20 Hz), beta2 (20–30 Hz) [9] and gamma (30–45 Hz). Each wave can be termed as a clock signal for the other body organs for proper functioning and also for the synchronization. Each wave is dominant for a particular activity. In order to analyze the effect of Radio frequency radiations emitted from the mobile phones on these waves, various parameters have been considered. As EEG depicts the non-linear and chaotic behavior hence, non-linear methods also have been utilized to detect the changes in it.

Majority of research work reported in literatures are to know the effect, mainly on the alpha waves. Some researchers do agree that alpha wave get affected due to mobile phone radiations. Others have also reported the effects on the delta waves during the sleep times. Many researchers have also studied the biological effects of mobile phones radiations on students, urban and rural people, etc. Studies have also been done on the animals and found that due to radiations exposure there is an adverse effect on their sleep pattern [10]. The outline of this paper is as follows. Section 1 gives the introduction; section 2 gives the review of researches done on this area whereas section 3 deals with materials and methods. Results and discussions are provided in section 4 and in section 5, conclusions have been presented.

2. Related study

Survey was carried out on the available literatures mainly presenting various facts about exposure impact. For the benefit of readers, extract of some of the important references are presented. Roggeveen *et al* [11] found a

Figure 3. Acquired EEG signal.

significant effect of mobile phone radiations on almost all brain regions and showed increase in alpha, beta, and gamma activity. Reported experimental study found that use of mobile phone on right ear increases more upper beta power leading to muscular discomfort and anxiety [9]. Isa *et al* [12] experimented on the alpha and beta brain waves showed no decrease in the brain wave power during exposure. Various research studies have also been done on the impact of mobile phone radiations on epileptic subjects which reports on a decrease in the spectral energy of alpha wave at the occipital region and increase in energy for all other brain waves in case of epileptic subjects [13]. Because of the nonlinear nature of the EEG signals, various other algorithms have been employed to measure the nonlinearity, complexity. Hinrikus *et al* [14] studied the effect of low frequencies microwave radiation on EEG and found significant changes in alpha and beta bands but no effect is seen on theta wave. Smitha *et al* [15] used fractal dimension algorithm and used mobile phone at different position and analyzed a change in the fractal dimension i.e., change in the complexity of EEG. Nicolas Perentos *et al* [16] reported decrease in the alpha band due to the mobile phone radiations. Isa *et al* [17] in their paper concluded that with the radiations from mobile phones

Table 1. Largest Lyapunov exponent.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	0.009708	0.012961	0.017508	0.012473	0.014182	0.33	0.07	0.52	0.308
C4P4	0.011025	0.01555	0.019521	0.013892	0.013766	0.33	0.07	0.52	0.308
F3C3	0.004789	0.005585	0.004786	0.006177	0.007231	0.682	0.999	0.651	0.281
F4C4	0.011512	0.008222	0.007392	0.009135	0.008797	0.315	0.296	0.504	0.364
F7T3	0.012158	0.009238	0.016246	0.01197	0.007485	0.65	0.643	0.969	0.409
F8T4	0.012353	0.010554	0.014635	0.017404	0.017546	0.607	0.659	0.438	0.637
FP1F3	0.013569	0.005501	0.017235	0.010964	0.00796	0.133	0.605	0.672	0.201
FP1F7	0.01368	0.008319	0.020042	0.016676	0.00998	0.268	0.478	0.692	0.39
FP2F4	0.011462	0.004678	0.012292	0.011491	0.005286	0.055	0.892	0.996	0.129
FP2F8	0.012976	0.010615	0.015177	0.014985	0.007444	0.589	0.715	0.71	0.12
P3O1	0.017188	0.015481	0.022327	0.019256	0.019953	0.692	0.546	0.539	0.658
P4O2	0.019896	0.032523	0.016155	0.013417	0.012809	0.541	0.701	0.252	0.332
T3T5	0.014581	0.009754	0.01663	0.015053	0.012223	0.378	0.778	0.899	0.661
T4T6	0.010817	0.01265	0.021046	0.013573	0.013073	0.602	0.14	0.594	0.599
T5O1	0.01255	0.007704	0.018127	0.010937	0.016046	0.085	0.491	0.672	0.384
T6O2	0.018908	0.02686	0.018323	0.00871	0.010877	0.67	0.947	0.31	0.441

Table 2. Approximate entropy.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	0.619731	0.635046	0.62055	0.638077	0.626812	0.316	0.968	0.406	0.703
C4P4	0.6277	0.626369	0.608665	0.632023	0.633527	0.903	0.435	0.824	0.767
F3C3	0.609308	0.620915	0.635512	0.629146	0.618954	0.597	0.352	0.53	0.735
F4C4	0.621608	0.606773	0.582973	0.628208	0.619073	0.521	0.135	0.815	0.927
F7T3	0.590858	0.577415	0.580596	0.607385	0.613004	0.716	0.651	0.587	0.375
F8T4	0.616069	0.622573	0.604108	0.630585	0.639565	0.865	0.571	0.74	0.432
FP1F3	0.491292	0.496685	0.520873	0.5189	0.520619	0.893	0.36	0.538	0.416
FP1F7	0.506208	0.495815	0.532458	0.514808	0.536712	0.817	0.412	0.83	0.31
FP2F4	0.565492	0.554827	0.551054	0.545812	0.563673	0.797	0.71	0.657	0.965
FP2F8	0.574488	0.566915	0.562427	0.56425	0.574115	0.827	0.691	0.79	0.989
P3O1	0.626381	0.649881	0.608312	0.644481	0.654665	0.12	0.434	0.492	0.177
P4O2	0.643304	0.641854	0.617804	0.637908	0.632669	0.923	0.218	0.847	0.571
T3T5	0.609773	0.632669	0.602327	0.636696	0.631935	0.25	0.586	0.262	0.249
T4T6	0.606796	0.634212	0.596238	0.623731	0.635938	0.193	0.637	0.557	0.229
T5O1	0.617642	0.642404	0.612692	0.655792	0.677962	0.172	0.811	0.239	0.024*
T6O2	0.648808	0.670827	0.635412	0.661381	0.653673	0.297	0.629	0.486	0.801

*Significant values.

there is an imbalance in both left and right brains. Murat [18] have also studied the alpha brain waves and found significant decrease in the alpha waves. Some studies also showed that continuous or pulsed radio frequency exposures do not cause change in the alpha brain wave [5]. The experiment performed separately on both sides of brain showed reduced symmetry between parts of the brain and reduced correlation between beta and alpha waves after the mobile phone radiation exposure [19]. Luis *et al* [20] studied the effects of cell phone radiation on the EEG spectra of epileptic patients and found that there was an

increase in beta and gamma power compared to a normal non-exposed persons. Thermographic analysis has also been done by Vorst *et al* [21]. They reported an increase in the temperature at the surface of ear and nearby in the range 1.0 to $2.4 \pm 0.2^\circ\text{C}$. Similarly Piuze *et al* [22] did an analysis of effect of radiations at mobile communication frequencies on child and adults models on the basis of on the Specific Absorption Rate (SAR) value and reported that the level specified increases in case of child. Lin [23] studied that those students who utilize mobile phone more in chatting and doing SMS show less pick up, delayed and

Figure 4. Approximate entropy and Channel-wise impact.

inaccurate responses [23]. Ilvonen *et al* [24] analyzed the effect of magnetic field induced through GSM mobile phones was considerably lower than the basic restriction limit given. The biological effects of mobile phone radiations studied in literature includes anxiety, sleep disorders, memory loss, pain in ear and temperature rise [25] in surrounding nerves, complicated birth and miscarriages in case of pregnant woman, effect on eyes [26]. In contrast to the research on increase in the alpha band power, in 2007 Perentos *et al* [27] found no significant change in the alpha power due to mobile phone radiations. Lin [28] has done various experiments on the sleep activity changes by exposure to the GSM mobile phone radiations. The author found inconsistent results in the sleep behavior. Researches have also been done on the micro structure of sleep and reported no effect due to GSM and WCDMA mobile

phones [29]. The research has also resulted in favor of these radiations, by showing better correlation between delta and theta brain waves after exposure and hence improved brain synchronization [30]. The GSM effect on brain is high as the power spectral density (PSD) of EEG signal is more when exposed to GSM mobile phone as compared to CDMA network phone [31]. The mixed reports motivated the authors to have a close look into the effect on EEG by conducting experiments in users' realistic conditions.

3. Materials and methods

3.1 Subjects

This study has been conducted on 75 (57 males and 18 females) young and healthy students studying in post graduate courses at National Institute of Technical Teachers Training and Research, Chandigarh, India. The mean age of the subjects is 22.2 years with standard deviation of 2.27 years. The subjects' daily usage of mobile phones is between 2–3 h. The subjects are healthy and not on any kind of medicine. While recordings are done, these subjects used their 2G and 3G mobile phones. In the experiments, Nokia, Samsung, Panasonic and Motorola mobile phones having SAR value between 0.67 and 1.14 W/kg are used by the subjects. The recordings are done when the subjects made their routine calls. So no external or any kind of RF exposure is given. Informed consent has been obtained individually from all the participants included in the study.

Table 3. Correlation dimension.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	2.081912	2.123804	2.079019	2.085765	2.065169	0.494	0.893	0.898	0.507
C4P4	2.117642	2.121315	2.12835	2.113377	2.100565	0.838	0.587	0.874	0.481
F3C3	1.850623	1.908758	1.836592	1.856327	1.851708	0.443	0.502	0.866	0.972
F4C4	1.907273	1.897954	1.850465	1.896838	1.879673	0.787	0.109	0.834	0.55
F7T3	1.914812	2.006081	1.848527	1.894096	1.849254	0.329	0.11	0.62	0.135
F8T4	1.95965	1.965142	1.950662	1.963335	1.907988	0.858	0.778	0.93	0.176
FP1F3	1.821912	1.905673	1.793927	1.850208	1.815442	0.2	0.43	0.612	0.893
FP1F7	1.898312	1.965888	1.846265	1.909642	1.862119	0.296	0.148	0.833	0.4
FP2F4	1.808996	1.852881	1.782369	1.809427	1.796762	0.609	0.472	0.994	0.778
FP2F8	1.914862	1.942169	1.917223	1.944631	1.900677	0.327	0.951	0.601	0.754
P3O1	2.077715	2.2027	2.110981	2.104835	2.110973	0.123	0.255	0.405	0.405
P4O2	2.099054	2.090773	2.08345	2.089773	2.043246	0.714	0.609	0.826	0.11
T3T5	2.030035	2.116596	2.034423	2.042296	2.015485	0.237	0.906	0.698	0.647
T4T6	2.025527	2.108208	2.033419	2.029796	2.017158	0.285	0.774	0.913	0.784
T5O1	1.929312	2.0555	1.971462	1.969208	1.972819	0.103	0.08	0.195	0.264
T6O2	1.987658	2.041146	2.000962	1.978512	1.950792	0.384	0.691	0.804	0.236

Table 4. Hurst exponent.

Channel	Mean					p-Value			
	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	0.67078	0.71531	0.69472	0.67788	0.68517	0.131	0.33	0.842	0.669
C4P4	0.66278	0.660177	0.706404	0.698258	0.665215	0.92	0.149	0.31	0.927
F3C3	0.77421	0.783369	0.736092	0.699165	0.76941	0.77	0.159	0.064	0.885
F4C4	0.69396	0.745392	0.756815	0.768335	0.7517	0.089	0.014*	0.014*	0.02*
F7T3	0.73179	0.825796	0.783092	0.765958	0.781077	0.018*	0.031*	0.296	0.13
F8T4	0.73331	0.75355	0.771096	0.758869	0.738085	0.499	0.168	0.427	0.828
FP1F3	0.78238	0.825581	0.804754	0.7755	0.766592	0.131	0.364	0.801	0.571
FP1F7	0.77450	0.807381	0.778738	0.775992	0.772904	0.273	0.889	0.961	0.957
FP2F4	0.79990	0.787127	0.781554	0.781042	0.773027	0.507	0.451	0.431	0.239
FP2F8	0.76183	0.793592	0.786273	0.749473	0.765573	0.279	0.434	0.627	0.896
P3O1	0.75805	0.737277	0.698181	0.732008	0.695985	0.418	0.033*	0.349	0.096
P4O2	0.69652	0.699262	0.718419	0.702231	0.708735	0.938	0.429	0.843	0.676
T3T5	0.74845	0.761519	0.747931	0.769342	0.758446	0.691	0.985	0.431	0.729
T4T6	0.70300	0.734008	0.703788	0.720196	0.747104	0.396	0.974	0.626	0.221
T5O1	0.81837	0.764973	0.755242	0.786258	0.744262	0.038*	0.025*	0.369*	0.013*
T6O2	0.71648	0.784142	0.775635	0.716673	0.730512	0.065	0.038*	0.994	0.635

*Significant values.

Figure 5. Hurst Exponent Channel-wise impact.

3.2 Protocol

The EEG acquisition is done in the morning before 8 a.m. and classified as: State when no mobile communication is going on i.e., the subject is in a relax mode, the EEG signal so acquired is called normal or ideal mode signal. Other states are when the subjects used mobile phones in GSM network (2G) and WCDMA network (3G) in transmitting and receiving modes. Tx—when the call is initiated by the subject and is called transmission mode, Rx—when the call is received. The sequence of recording is not fixed and is random as the state comes. The experiment is done in a laboratory where there is no localized generation of EM signals except the signal

available from the mobile towers responsible for establishing usual mobile communications. The same is ensured by using a Boonton Power meter Model no. 52018 having a sensitivity of nano watts. The EEG signal of the subject is recorded without a mobile phone and the baseline is defined for the concerned subject based on the EEG recorded in the absence of the use of mobile phone. The subject is then exposed to EM radiations by allowing use of mobile phone both in transmission as well as receiving mode. The recorded EEG signal is compared with the baseline signal as stated above and the variations so obtained are analyzed. As a pre-filtering process to ensure that the cable of the EEG nodes are not picking up any external signal from the mobile, the experiment is performed by putting the mobile on a phantom model and fixing the sensors on the phantom head to ensure that proper shielding of the EEG sensor node and wires exist. The set-up with dummy and the subsequent recorded EEG with dummy is a preprocessing method carried out to eliminate the noise arises due to picking of the signal by the EEG wires externally from the mobile phones. The field intensity is measured using a Boonton power meter Model no. 52018 before the acquisition is done. No appreciable field intensity variation is observed till 10 min. Hence, the measurement is carried out up to 5 min therefore, is in a non-varying situation. EMI shielding is an essential experimental need to ensure accurate study in this type of research where the signal level is quite low and is distributed over various bands of frequency. In this experiment, 16 channel EEG recorder is used. In order to shield the external signal, each channel is connected to phantom separately i.e., when channel C3P3 is connected,

Table 5. Delta power.

Channel	Mean					p-Value			
	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	70.04701	81.15355	74.89917	66.71412	54.21314	0.635	0.801	0.872	0.388
C4P4	52.48661	61.1039	64.00522	70.37273	53.31393	0.702	0.498	0.508	0.955
F3C3	66.99561	40.59951	48.45803	69.06251	79.31853	0.304	0.416	0.963	0.837
F4C4	89.54494	69.46851	63.76374	393.4787	59.29394	0.598	0.472	0.353	0.489
F7T3	121.3372	194.2645	77.24941	95.39073	155.5642	0.375	0.114	0.437	0.708
F8T4	67.16519	129.1135	63.60401	124.1656	75.60461	0.103	0.711	0.177	0.706
FP1F3	178.6189	195.9787	143.2456	285.8682	158.2611	0.814	0.414	0.303	0.749
FP1F7	192.5157	349.0423	157.4349	202.0418	201.1452	0.298	0.363	0.829	0.887
FP2F4	129.3849	138.93	109.9932	456.1884	154.3886	0.809	0.337	0.308	0.444
FP2F8	137.2698	206.1465	134.7982	132.1314	193.7105	0.419	0.907	0.853	0.325
P3O1	105.0073	119.2044	121.0279	82.53108	75.44238	0.598	0.565	0.436	0.232
P4O2	267.4399	110.1149	95.13507	109.7379	81.46641	0.288	0.31	0.383	0.281
T3T5	99.3516	99.66959	91.22184	89.3623	84.98933	0.992	0.572	0.484	0.623
T4T6	106.8207	99.91615	74.32863	62.82903	92.15032	0.74	0.207	0.216	0.741
T5O1	105.1323	160.4738	127.6208	111.2924	97.61465	0.479	0.655	0.807	0.826
T6O2	231.4494	96.2922	66.33618	69.06804	65.35798	0.368	0.331	0.315	0.294

Figure 6. Delta power channel-wise impact. **Figure 7.** Theta Power Channel-wise impact.

no other sensor node is connected and so on for all the other 16 channels. After each channel is tested separately, the channels are connected sequentially and are verified for any external signal. Both approaches i.e., measuring the absolute EMI for each channel and average measured over duration of 10 min yield no EMI due to connecting wire or sensor nodes. The nano-watt power meter shows no sign of any signal being picked up by the sensor node/connecting wire of EEG. The same was shown to the Senior Cardiologist. Hence, the variations observed in brain waves when mobile phone is used by subjects are due to RF radiation absorbed in the head but not by any external signal through connecting wires/sensor node.

3.3 Data acquisition

EEG signals are acquired by placing 20 electrodes on the scalp in 10–20 international system configuration using RMS Maximus 24–32 set-up. The F, T, P, C and O stands for the part of the scalp as frontal, temporal, Parietal, central and Occipital, respectively [8]. Even numbers 2, 4, 6, etc. refer to the right position and odd numbers 1, 3, 5, etc. refer to the left positioning of electrodes on the scalp of the brain [8]. Electrode impedances are below 5K ohm at the start of the recordings. As shown in figure 1, the subject is in normal mode i.e., recording is done without mobile phone and in figure 2 the subject is in communicating

Table 6. Theta power.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	18.31366	15.49625	21.96054	16.02575	16.17433	0.125	0.325	0.384	0.407
C4P4	16.78444	15.42868	16.26767	16.53605	16.85979	0.152	0.452	0.822	0.948
F3C3	6.856492	6.739665	7.125281	7.651981	9.222648	0.743	0.411	0.444	0.297
F4C4	8.878698	7.272535	7.403224	25.5249	8.379102	0.237	0.391	0.336	0.791
F7T3	24.1441	12.9009	6.856674	7.795781	11.21104	0.339	0.321	0.353	0.483
F8T4	7.267655	7.52023	6.963392	8.341928	8.509558	0.794	0.775	0.551	0.444
FP1F3	8.002909	7.538124	8.457346	9.398506	7.622516	0.735	0.591	0.641	0.813
FP1F7	8.370889	8.321811	9.463854	10.04721	10.24994	0.97	0.157	0.588	0.421
FP2F4	6.600333	5.767204	6.854813	35.7491	6.97565	0.367	0.773	0.321	0.748
FP2F8	10.82959	9.505129	10.15997	9.648896	9.883322	0.553	0.765	0.721	0.768
P3O1	19.83688	16.3249	21.79547	19.19764	17.11702	0.023*	0.672	0.852	0.276
P4O2	30.0366	13.95981	12.90312	13.84544	13.6298	0.217	0.204	0.229	0.224
T3T5	19.3111	13.57945	11.8235	12.06555	11.22318	0.31	0.362	0.374	0.334
T4T6	11.25739	9.170726	9.525009	9.883831	11.66336	0.123	0.234	0.373	0.852
T5O1	10.0458	10.08923	9.621125	12.74459	11.40402	0.942	0.521	0.263	0.119
T6O2	32.3783	9.858688	9.897941	9.260502	9.055266	0.321	0.322	0.308	0.303

Table 7. Alpha power.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Rx	2G Tx	3G Rx	3G Tx
C3P3	111.6407	114.8864	125.6605	129.7871	121.4189	0.511	0.031*	0.042*	0.098
C4P4	94.67723	104.7858	109.8014	113.0054	109.9707	0.081	0.015*	0.033*	0.038*
F3C3	21.43226	21.41355	21.8796	23.87838	24.14033	0.99	0.636	0.3	0.356
F4C4	27.55644	27.20852	27.65807	114.2335	31.0259	0.903	0.968	0.306	0.335
F7T3	34.32952	23.99076	17.68259	20.06277	20.14169	0.369	0.355	0.431	0.442
F8T4	22.1681	24.11161	24.64295	26.78337	26.34563	0.217	0.056	0.077	0.057
FP1F3	6.956062	6.478942	6.503286	8.326383	6.793317	0.612	0.704	0.575	0.915
FP1F7	10.07723	10.16053	10.2453	12.07927	11.80021	0.919	0.88	0.409	0.292
FP2F4	6.232504	5.475342	5.977054	119.0231	5.785321	0.448	0.786	0.152	0.686
FP2F8	15.01684	13.9011	13.89094	14.90652	14.32487	0.688	0.751	0.976	0.855
P3O1	67.90402	63.44351	73.91536	68.44906	68.68106	0.1	0.328	0.87	0.852
P4O2	92.77627	56.00431	59.92079	60.18076	57.75913	0.003*	0.007*	0.01*	0.004*
T3T5	51.35655	49.09019	47.13861	48.50372	47.13089	0.715	0.562	0.715	0.593
T4T6	51.40668	50.39165	52.83726	54.71222	54.10506	0.123	0.234	0.373	0.852
T5O1	21.14848	24.88421	24.40096	29.4612	26.58303	0.091	0.074	0.045*	0.071
T6O2	57.32906	24.17881	23.74197	25.93086	25.12119	0.352	0.347	0.381	0.368

*Significant values.

mode. The subjects are asked to close the eyes to avoid noises due to eye blinking.

The EEG signal acquired is shown in figure 3. After acquisition, the signal is filtered through 1 Hz filter; 50 Hz filter and EMG filter for the various noises. The sampling frequency is 256 Hz. The signal is then taken into excel format and processed for various parameters using programs code written in MATLAB. For calculating the power, the EEG is first extracted into all brain waves viz.

delta, theta, alpha, beta and gamma using IIR Butterworth band pass filter with lower and upper cut-off frequency at the specified range of each brain wave.

3.4 Methodology

The EEG raw data so recorded from all the five modes is analyzed for various linear and nonlinear parameters

as follows. The data after filtering is first extracted into excel format and then values for each channel for each parameter is calculated using the MATLAB codes. The analysis is done for Largest Lyapunov Exponent (LLE), Hurst Exponent, Approximate Entropy (ApEn), Correlation Dimension (CD) and Power for all the five brain waves. LLE is a parameter used to measure the chaos in the system or time signal and is a measure of stability. It is an average value of long data time series and denotes the overall characteristics of the data. It can be positive, negative and zero depicting the various states of the data. The system is stable if LLE is less than zero. When it is positive, it represents a chaotic condition and at boundary when equals to zero [32]. LLE is mostly used to find the non-linearity in the system. Approximate entropy (ApEn) gives the amount of irregularity in the signal. A high value of ApEn denotes higher irregularity and lower value denotes the regularity in the patterns of the signal [33]. The embedding dimension 'm' in the algorithm of ApEn is the length of the segments for the input series that are compared and 'r' is the threshold that is fixed for the comparison of the segments [34]. The ApEn value is calculated in the steps as explained in [35]. High value of correlation dimension (CD) denotes the signal is more complex and less similarity in the data [36]. Hurst Exponent (HE) tells about the smoothness of the time series data and is dependent on the past samples [37]. If the value is close to zero, it means smoothness in the data is less [37]. The EEG signal is also extracted into the five brain waves namely delta, theta, alpha, beta and gamma by using band pass filter for each channel and for each subject. Their mean power is calculated. The mean values of each parameter is calculated and compared with the ideal value for each channel. The results so obtained are then statistically analyzed using SPSS software [38] version 20. The mean values are compared in 2-tailed t-test and the p-value [39] i.e., probability value, below 0.05 is taken as significant which means that the actual change in the statistics is significant and is to be considered and the null hypotheses is rejected. In this research work, the null hypothesis is that there is no significant difference in the mean of the two variables.

4. Results and discussion

The mean values of all parameters are taken and the results so obtained are depicted in tables 1 to 9 as shown. The mean values for all modes i.e., normal, 2GRx, 2GTx, 3GRx, and 3GTx have been presented and corresponding to each mode their 'p' value from the statistical analysis is shown. The values of Lyapunov exponent depicted in table 1 shows the behavior of the system. The positive Lyapunov exponent depicts the chaotic situation and the

negative exponent depicts the regular situation [36]. The higher value of LLE depicts more chaotic behavior. In 2GRx, LLE value is higher in 2GTx mode mostly at all channels and low in 2GRx mode. The highest value is at temporal, occipital and all parietal sections in the brain during 2G transmission mode of communication. But the value is not significantly high at any of the channel. Approximate entropy as depicted in table 2, increases with the use of mobile phone but not significant to make a claim except during 3GTx at T5O1 channel. The increase in approximate entropy shows that the complexity of the signal increases with the exposure. There is higher change in the FP2F4 and F4C4, as shown in figure 4 which is near to the right ear i.e., the side on which mobile phone was held.

This supports the findings of Ilvonen *et al* [24] that current drops rapidly when moving away from the source, so the effect is near to the source. It has been

Figure 8. Alpha power channel-wise impact.

Figure 9. Beta power channel-wise impact.

found in [40] that EEG of Alzheimer's patient is less complex and the value of approximate entropy in them is significantly lower than the normal control group. Correlation dimension parameter defines the dimension of the signal and with the exposure there is no significant change in the dimension parameter. It is approximately same throughout as shown in table 3. Hurst Exponent as given in table 4 is significantly high at F4C4 during all the modes. At some channels its trend is on higher while on in other modes it is on the lower side. The value at

T5O1 is significantly low in all the modes. As shown in figure 5, the value is low at the occipital region and there is no change in the frontal part of the brain whereas it is high at the central and temporal part.

The delta wave prevails during the deep sleep. With the use of mobile phones, there is no significant change observed as depicted in table 5. When analyzing the individual channels on the brain in figure 6, it is observed that the values are higher at the right temporal

Table 8. Beta power.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Tx	2G Tx	3G Rx	3G Tx
C3P3	5.340967	5.4942	6.746587	4.177874	4.354117	0.797	0.208	0.549	0.502
C4P4	4.976798	5.969916	5.470431	5.611531	5.662853	0.02*	0.341	0.446	0.39
F3C3	1.621158	2.043488	1.706862	2.504427	1.959637	0.186	0.878	0.447	0.572
F4C4	4.020936	4.044444	1.622194	29.3114	2.208652	0.889	0.345	0.344	0.488
F7T3	9.88892	11.00887	3.207676	4.614556	3.495417	0.442	0.306	0.42	0.343
F8T4	3.395488	4.485198	3.142139	4.29439	3.514288	0.025*	0.826	0.68	0.941
FP1F3	2.691339	2.631254	0.967207	4.522112	2.000668	0.64	0.351	0.648	0.739
FP1F7	2.363549	2.473873	1.176674	4.548404	2.088602	0.474	0.407	0.572	0.871
FP2F4	1.934579	1.24225	1.256921	28.6646	1.393871	0.376	0.363	0.317	0.529
FP2F8	6.065513	5.79361	2.239224	3.744087	2.218779	0.791	0.407	0.644	0.407
P3O1	10.46362	10.23068	9.782411	9.523682	9.707432	0.742	0.741	0.77	0.776
P4O2	22.36636	11.1847	4.627215	4.566124	4.103068	0.334	0.195	0.195	0.184
T3T5	16.76994	18.83357	4.138632	4.911315	3.661646	0.232	0.329	0.362	0.322
T4T6	3.636873	4.050971	2.614173	3.213311	2.758881	0.101	0.53	0.813	0.608
T5O1	6.184431	6.593343	5.534869	8.119351	7.701566	0.469	0.304	0.347	0.254
T6O2	17.33462	6.211035	5.470911	4.60255	4.563722	0.342	0.311	0.277	0.276

*Significant values.

Table 9. Gamma power.

Mean						p-Value			
Channel	Normal	2G Rx	2G Tx	3G Rx	3G Tx	2G Tx	2G Tx	3G Rx	3G Tx
C3P3	0.318761	0.329435	0.343972	0.188201	0.184634	0.841	0.477	0.433	0.339
C4P4	0.266914	0.341622	0.305035	0.296963	0.276066	0.043	0.491	0.707	0.859
F3C3	0.071072	0.083921	0.063345	0.124251	0.074329	0.473	0.851	0.546	0.94
F4C4	0.25874	0.167815	0.058373	1.31363	0.098422	0.334	0.319	0.369	0.434
F7T3	2.156966	0.830969	0.188178	0.26338	0.192301	0.326	0.326	0.346	0.33
F8T4	0.198848	0.250706	0.157893	0.246277	0.177174	0.185	0.68	0.778	0.858
FP1F3	0.171421	0.096915	0.031164	0.304785	0.098226	0.309	0.325	0.658	0.635
FP1F7	0.148836	0.106567	0.039518	0.301814	0.099475	0.382	0.345	0.6	0.704
FP2F4	0.129758	0.072329	0.058892	1.29905	0.066483	0.432	0.302	0.32	0.41
FP2F8	0.402316	0.221096	0.116385	0.222992	0.100202	0.442	0.395	0.627	0.37
P3O1	0.731965	0.630013	0.61786	0.617347	0.561138	0.125	0.418	0.674	0.407
P4O2	0.93986	0.392144	0.208449	0.203325	0.160679	0.187	0.228	0.228	0.202
T3T5	1.145913	0.595157	0.205202	0.232311	0.164414	0.36	0.337	0.352	0.323
T4T6	0.18442	0.171737	0.092316	0.138098	0.10774	0.762	0.469	0.739	0.659
T5O1	0.411858	0.437174	0.353302	0.53835	0.443261	0.595	0.257	0.442	0.666
T6O2	0.613325	0.394024	0.342357	0.256884	0.236904	0.415	0.313	0.191	0.173

Figure 10. Gamma power channel-wise impact.

T4, F4, F8, FP2, left occipital T5, O1, and left frontal F7, FP1.

The theta power is increased at T4, F8, T5, O1 and F7, FP1. The decrease in the theta power is observed as shown in figure 7.

In the different modes of transmission, significant decrease in theta power is observed at channel P3O1 in 2GRx mode. Otherwise, at other modes, the response to the radiations is mixed and only in 2GRx mode the theta power is decreased with the radiations as depicted in table 6. The alpha power has increased at many regions such as T4, T6, C4, P4, F7, FP1, T5, O1, F3 and C3 with significant decrease at P4O2 in all the modes as shown in table 7. When examined channel-wise, it is observed that there is increase at the right ear lobe side and left occipital side extending to the left frontal as shown in figure 8.

The increase in the alpha wave is the indication of relaxed state which is in agreement with Lee *et al* [41] who suggested the use of pulsed magnetic field (pMF) as a stimulus to increase the alpha activity. The beta power is depicted in table 8 and figure 9 and has similar behavior as alpha power except at F7 and FP1.

The gamma power has significantly increased at C4P4 in 2GRx mode as depicted in table 9. As shown in figure 10, the gamma power is increased only at T5, O1 at the occipital region and decreased in rest of the part. At T4, F8 i.e., right temporal part and T5, O1, left occipital part have experienced high power due to radiations.

The changes in the brain waves due to RF radiations may bring severe oxidative stress that may cause neurons degeneration [41]. As discussed in [42, 43], the electromagnetic radiations can be used for the treatment of neurodegenerative diseases. Similarly, extensive research on this area can be done and there is a strong belief of the authors that there can also be a ray of hope for coma patient also. Mobile phone radiations come in the non-ionization radiations so they do not cause any genetic changes [44] but

other thermal effects cannot be ignored. Sayer [45] reported that an alteration in EEG which can lead to the structural and functional changes in the brain that affects the cognition, mood and behavior.

5. Conclusion

The present paper covers an extensive study on the effects on various brain waves due to exposure to mobile radiations. A large data base of 75 healthy subjects is analyzed to study the impact of RF radiations on five brain waves. Significant changes have been observed in almost all the brain waves at the different channels. The changes are observed on the right temporal side towards the right ear to which the mobile phone is held. The left occipital region T5, O1 also showed high values of all parameters measured except Hurst exponent due to these radiations. As seen from the results, there is increase in the values of all the parameters at T4, F8 at the right side of the brain near to the right ear where the mobile phone is held. Also the higher alpha power value is observed at T5, O1 and F7, FP1 channels. It can also be seen that the effect is extending clearly in terms of power and other nonlinear parameters not only the side on which phone is held, but also extending towards the other interior regions of the brain. These parts of the brain are responsible for the emotional memory, verbal understanding, visual processing and attention. In this study, the maximum exposure duration is of 5 min. With this short duration of exposure, visible and measurable variations are observed in all the five brain waves. But in the present time, mainly the youngsters are in extensive use of mobile phones thus may have more adverse effects. Further, clinically supported research is required to quantify such adverse impacts.

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