Health Effects of 5G Base Station Exposure: A Systematic Review

TASNEEM SOFRI\(^1,2\), (Graduate Student Member, IEEE), HASLIZA A RAHIM\(^1,2\), (Senior Member, IEEE), MOHAMEDFAREQ ABDULMALEK\(^3\), (Member, IEEE), KHALIYAHUSNA ABD RANI\(^4\), MOHD HAFIZI OMAR\(^2\), MOHD NAJIB MOHD YASIN\(^1,2\), (Member, IEEE), MUZAMMIL JUSOH\(^1,2\), (Senior Member, IEEE), AND PING JACK SOH\(^5\), (Senior Member, IEEE)

\(^1\)Advanced Communication Engineering, Centre of Excellence (ACE), Universiti Malaysia Perlis, Kangar 01000, Malaysia
\(^2\)Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis, Arau 02600, Malaysia
\(^3\)Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, Dubai 20183, United Arab Emirates
\(^4\)Institute of Engineering Mathematics, Faculty of Applied and Human Sciences, Universiti Malaysia Perlis, Arau 02600, Malaysia
\(^5\)Centre for Wireless Communications (CWC), University of Oulu, 90570 Oulu, Finland

Corresponding author: Hasliza A Rahim (haslizarahim@unimap.edu.my)

This work was supported by the Malaysian Communications and Multimedia Commission (MCMC) under Grant 2020/01/001. The work of Ping Jack Soh was supported by the Academy of Finland 6G Flagship under Grant 318927.

ABSTRACT The Fifth Generation (5G) communication technology will deliver faster data speeds and support numerous new applications such as virtual and augmented reality. The additional need for a larger number of 5G base stations has sparked widespread public concerns about their possible negative health impacts. This review analyzes the latest research on electromagnetic exposure on humans, with particular attention to its effect on cognitive performance, well-being, physiological parameters, and Electroencephalography (EEG). While most of their results indicated no changes in cognitive function, physiological parameters, or overall well-being, the strength of the EEG alpha wave is noticed to vary depending on various aspects of cognitive functions. However, the available studies have not investigated the health effects resulting from exposure from the 5G mobile phone and base station antennas from 700 MHz to 30 GHz on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG of adults. There is a need for such research regarding this current emerging technology. Such studies are significant in determining whether 5G technology is indeed safe for humans.

INDEX TERMS Radiofrequency electromagnetic fields, public health, 5G exposure, bioelectromagnetics, base station, mobile phones, antenna and propagation, cognitive function, electroencephalography, electromagnetic hypersensitivity, well-being, human studies, health.

I. INTRODUCTION

The introduction of the Global System for Mobile Communication (GSM) in the 1990’s, Universal Mobile Telecommunication System (UMTS) in 2000, Long Term Evolution (LTE) in 2010 and the 5G mobile networks in 2020 have dramatically increased the use of Mobile Phones (MPs). Mobile services will be used by over three-quarters of the world’s population, or 5.7 billion people. 5G will offer needed wireless infrastructure to keep up with the constant increase in data consumption and will satisfy the demands by innovative applications such as networked and autonomous automobiles, smart factories, and cities, etc. Revolutionary technologies such as beamforming and Massive Multiple-Input Multiple-Output (MaMIMO), besides innovative new radio coding software will enable 5G to support a considerably larger number of terminals (up to one million per square kilometer) with much greater data speeds (peak rate up to 20 Gbps), extremely low latency (no more than 1 ms), and exceptionally high dependability (99.999%). This provide users with a high quality of service while also enabling extremely dependable enormous communication between devices [1].
In comparison to Second through Fourth Generation (2G to 4G) mobile technologies (such as GSM, UMTS, and LTE), the 5G New Radio (NR) technology utilize a huge span of spectrum which are divided into two broad ranges: the first spanning from 410 MHz to 7.125 GHz (known as the ‘sub-6 GHz’ frequency range), and the second from 24.25 GHz to 52.6 GHz (known as the millimeter-wave ‘mmWave’ frequency range). Furthermore, MaMIMO will support up to hundreds of antennas to allow many users to share the same time-frequency slot, increasing network capacity and improving transmission range while reducing power consumption [2]. The signal at the receiver will be one of the primary technological advancements improved in 5G NR [3]. MaMIMO system employs many transmit antennas at the Base Station (BS) as this is enables them to recover information even with a poor Signal-to-Noise-Ratio (SNR) and highly noisy channel estimates. At least an order of magnitude of additional antennas is expected in MaMIMO systems compared to existing cellular systems.

Electromagnetic Fields (EMF) exposure potentially affects the human body, including ‘heating’ of the skin. The temperature of a skin’s outer surface is usually between 30°C and 35°C. The pain detection threshold temperature for human skin is around 43°C [4] and any temperature surpassing it can cause a long-term injury. Heating is a significant influence since it can result in cell damage and protein induction. High-frequency EMF is also known to influence the sweat glands (which may serve as helical antennas), peripheral nerves, the eyes and the testes, and may have indirect effects on other organs in the body [5]. The Federal Communications Commission (FCC) of the United States (US) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) established recommendations for the maximum quantity of EMF radiation that may be administered to a person’s body. It is recommended by the FCC’s guideline that the Specific Absorption Rate (SAR) is averaged over 1 gram (g) of tissue, whereas the ICNIRP’s guideline is averaged over 10g. Recommendation by the FCC looks to be stricter, whereas 2-3 times energy absorption is permitted by the ICNIRP. In addition to that, the US Food and Drug Administration (FDA) states that the current knowledge of the negative effects of EMF emissions on human health is insufficient to determine whether exposure to the emissions is safe or not, and that more research is needed to fill in the gaps in the literature on human health safety in wireless systems use [6]. Meanwhile, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) categorizes EMF exposure as a ‘possibly carcinogenic to humans’ (Group 2B) [7]. The ICNIRP exposure recommendations [8] establish a maximum power density of 10 W/m² for the general population between 10 GHz and 300 GHz, measured as an average across any 20 cm² of exposed area. Moreover, the spatial maximum power density averaged over any 1 cm² shall not exceed 200 W/m². The uncontrolled power density exposure limit for FCC between 6 GHz to 100 GHz is also 10 W/m², which in general is to be considered as a spatial peak value [4], [9]. However, spatial peak is not a well-defined quantity, and the answer obtained will be dependent on the method used to measure exposure. Measurements will be averaged across the probe dimensions, and a suitable sample density will be required for calculations. Between 3 GHz to 100 GHz, the IEEE general public basic restriction on power density is 10 W/m² [10]. In the frequency range between 3 GHz to 30 GHz, the power density is to be spatially averaged over any contiguous area corresponding to 100λ², where λ is the free space wavelength of the Radiofrequency (RF) field. IEEE also specifies the maximum spatial peak power densities of 18.56f^0.699 W/m² at frequencies between 3 GHz and 30 GHz, where f is the frequency in GHz. However, IEEE specifies neither average area nor spatial sampling density for this limitation, and measurements using a minimum spatial sampling density of four samples per wavelength was performed in [6].

The accelerating deployment of telecommunication towers and base stations raises public concerns about possible health effects of the radiation coming from those structures in the recent few years. In Malaysia, for example, demonstrations and complaints have been lodged by the public against the construction of telecommunication tower in their residential areas [11], [12]. Concerns regarding the harmful effects of radio frequencies on human health might potentially be a stumbling block to broaden 5G infrastructure deployment. The mmWave spectrum will be utilized to build a dense network of small picocells, resulting in the installation of many new radio transmitters [1]. The Engineering & Technology (E&T) Magazine recently that the UK government has published a guide for the public about 5G networks due to the increase of 5G conspiracy theories on social media platforms, including that the COVID-19 pandemic could be linked to the new networks in some way. The misinformation spread quickly and led to numerous accounts of people vandalizing 5G masts over this concern [13].

The necessity of a very high data rate in 5G necessitates an increase in signal power received at the user’s end, possibly increasing the electromagnetic radiation inflicted on the user in the vicinity [14]–[16]. Furthermore, three features of 5G which may potentially increase human EMF exposure further is explained as follows. Firstly, 5G aims to operate at higher frequencies (e.g., 28, 60, and 70 GHz) besides the existing lower frequency bands for cellular communications. However, as the frequency of EMFs increases, so does the rate of signal absorption into the human skin. Secondly, the variation in cell size between mmWave 5G, 4G, and 3.5G is a key suspect in increasing the level of human EMF exposure prior to the deployment of 4G, the 3GPP released 3.9G. There will be more transmitters in operation in the vicinity of the community due to the use of small cells in mmWave 5G. These BSs service smaller geographic regions and are consequently closer to human users. Among the three technologies, 5G communication systems feature the smallest cell diameter (200 m) with an Inter-Site Distance (ISD) of 100 m. This distance is also the maximum distance between a user and
a mmWave 5G BS. Finally, in 5G, directed beams are needed to solve the faster signal power attenuation due to higher operating frequencies. It is important to note that the major reason for implementing multiple-antenna systems is to enhance antenna gain. Due to the larger concentration of electromagnetic radiation, EMF has a better chance of penetrating deeper into a human body [17]. Most previous research have focused solely on the uplink, with little attention paid to EMF emissions generated by BSs in a 5G network, as illustrated in Figure 1. The uplink in 5G is described as the allocation of power resources among users via User Equipment (UE), i.e., MPs. Meanwhile, the downlink in 5G is defined as the power resource that is centralized inside the BSs. Due to the changes in coverage exposure area in mmWave 5G, the downlink may also pose a hazard to human health [18]. In summary, the changes due to the adoption of 5G mmWave are as follows:

i. increased carrier frequency operation
ii. reduction in cell size (resulting in an increase in the number of BSs)
iii. greater EMF energy concentration in an antenna beam

Various studies have reported the effects of Radiofrequency Electromagnetic Fields (RF-EMF) radiation on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG. They are primarily focused on wireless communication devices such as BS antennas operating in different frequency bands [10], [19]–[23], MPs [17], [24]–[27], Wi-Fi [10], Terrestrial Trunked Radio (TETRA) BS [28] and portable TETRA handsets [29]. To date, it is unclear whether RF-EMF field emitted by MP BSs affects well-being in adults, as the results from the existing studies on this topic are inconsistent. The health effects of RF-EMF due to 5G frequencies were studied [30] from 6 to 100 GHz on in vivo and in vitro biological structures. However, to the best of our knowledge, none of previous reviews focused on the health effects resulting from exposure from the 5G MP and BS antennas from 700 MHz to 30 GHz on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG of adults. Moreover, a recent study [18] highlighted that 5G radiation at 28 GHz may represent a hazard to human health, making such assessment urgently needed. This is significant in determining whether 5G technology is indeed safe for human.

II. LITERATURE SEARCH AND SELECTION

METHODOLOGY

The literature search was performed in May 2021 using keywords related to RF-EMF such as ‘radiofrequency’, ‘RF’, ‘electromagnetic field’, ‘EMF’, ‘mobile phone’, ‘cellular phone’, ‘2G’, ‘3G’, ‘4G’, ‘GSM’, ‘UMTS’, ‘LTE’. Besides that, more specific terms related to EEG and brain electrophysiological activity (such as ‘electroencephalogram’, ‘EEG’, waking electroencephalogram/EEG), ‘spontaneous electroencephalogram/EEG’, ‘electroencephalogram/ EEG at rest’, ‘alpha/β band/rhythm/frequency’, ‘8–12 Hz/8–13 Hz’, ‘power spectral density’, ‘cerebral/brain activity/physiology’, ‘human’), cognitive performance (such as ‘reaction time’, ‘RT’, ‘psychology’), well-being (such as ‘subjective symptom’, ‘well-being symptoms’, blood pressure’, ‘BP’, ‘heart rate’, ‘HR’, body temperature’, ‘BT’, ‘Electromagnetic Hypersensitivity (EHS)’, ‘non-EHS’).

Upon compilation of these literature, a pre-selection is performed based on the title and abstract of these English-language publications. Then, employing full text analysis, a more extensive examination of relevant papers was conducted, with studies chosen based on the following inclusion criteria:

- blind condition (single or double blind)/randomized/balance study with a cross-over design,
- IEI-EMF reported symptoms (non-EHS or EHS subjects),
- physiological parameter (blood pressure, body temperature or heart rate),
- subjective symptoms (well-being or visual analog scales),
- cognitive performance as experimental approach,
- investigation of the EEG technique and waking spontaneous EEG,
- radiofrequency range related to BS and MP technologies,
- radiofrequency range related to 5G technologies.

As a result, 33 studies (ten for cognitive performance, 13 for well-being and physiological and ten for EEG) were selected for inclusion in this review. The next section explains the findings from the literatures, followed by an analysis and discussion of the previous findings. In the following sections, the experimental protocols, materials and methods of each selected study, and parameters will be compared and discussed in the final section. These include the volunteer’s inclusion criteria and physiological measures, SAR, RF-EMF, exposure period, etc.

III. COGNITIVE PERFORMANCE

Healthy adult volunteers who described feeling a range of symptoms such as headaches in the proximity of RF sources
were studied in terms of cognitive function. Many studies have examined how MPs radiation affects cognitive performance using behavioral metrics. They include response speed and accuracy in a variety of tasks, as shown in Table 1. For instance, Preece et al. [31] tested the short-term and long-term memory, simple and choice response time, and sustained attention on a total of 15 participants, yielding a total of 15 dependent variables. \( N \) is defined as number of volunteers/subjects. Using a single-blind, counterbalanced, randomized crossover method, volunteers were exposed, or Sham exposed, to continuous or pulsed 915 MHz GSM-type transmissions for about 30 minutes. In the Choice Response Time (CRT) task, there was a statistically significant reduction in Reaction Time (RT) when exposed to the continuous signal. The impact was not followed by a decrease in response accuracy, indicating that it was not a speed-accuracy trade-off. Simple Response Times (SRTs) were unchanged, and word, number, and image recall, as well as spatial memory, were constant.

Exposure to a pulsed GSM signal had no significant impact. Koivisto et al. [32] evaluated at 48 individuals and used a variety of cognitive tests. Volunteers were exposed or Sham-exposed to a 902 MHz GSM signal using a single blind counter-balanced crossover setup. In basic RT and Vigilance (VIG) activities, slower RTs were reported [33], similar with the reported findings in [32]. Furthermore, during exposure, the time required to complete a mental arithmetic, Subtraction Time (SUB) assignment was reduced. A second research used a similar experimental design to evaluate the effects of GSM RF on the execution of a task with varying working memory demand [33]. A statistically significant reduction of RT was reported when the memory load was particularly demanding. However, a similar attempt to validate and expand the findings of both investigations failed [32], [33].

Curcio et al. [34] studied a small number of volunteers \( (N = 20) \) using various cognitive tests in a double-blind counterbalanced crossover design. The subjects were tested on four cognitive tasks, i.e., an acoustic SRT task, a visual search task, an arithmetic descending SUB task, and an acoustic CRT task. The results indicated that both SRT and CRT were reduced during exposure to a 902 MHz GSM signal than Sham exposure. However, an attempt by the same research group to replicate and confirm the finding was not successful, as no significant effects in the same SRT task was observed (the CRT test was not performed) [35]. Other studies also have failed to detect significant effects of mobile phone and BS signal exposure on the cognitive performance of human. Cinel et al. [17] replicated the effect of GSM MPs on attention and memory functions presented earlier in [32], [33] with a larger sample size \( (N = 168) \). However, the effect of exposure on any of the six cognitive tests as those performed by [32], [33] was far from significant.

Sauter et al. [29] found no evidence of a detrimental impact of a short-term EMF-effect of a TETRA hand-held transmitter on the cognitive performance of healthy young males. Computer tests on three distinct elements of attention (i.e., divided attention, selective attention, VIG) and working memory were used to assess cognitive functions. Recently, Vecsei et al. [36] observed the short-term RF-EMF exposure from 3G and 4G MPs. Similarly, the Stroop test revealed that these signals had no effect on the cognitive functioning of executive function measurements, processing speed, or selective attention. Table 1 summarizes the studies investigating the effects of RF-EMF exposure on cognitive performance and findings in literature.

### IV. ADULTS WITH EMF-ATTRIBUTED SYMPTOMS

Zwamborn et al. [37] first explored the subjective feelings and cognitive functions in a group of 36 people who claimed to have symptoms related to living near a GSM BS and a group of 36 healthy people in a research that used exposure comparable to that from a BS. As the groups differed in age and gender distribution, no comparisons could be conducted between categories; only within groups for periods with and without exposure could be performed. The individuals were exposed to a 1 V/m field at 900 and 1800 MHz (GSM signal), and 2100 MHz (UMTS signal). Using a double-blind design, each volunteer participated in three sessions, one of which was unexposed. Each exposure group had 24 individuals. Each session lasted 45 minutes, consisting of the exposure (during which cognitive skills were assessed), the questionnaire, and the break. The cognitive functions that were tested were RT, memory comparison, dual-tasking, selective visual attention, and filtering irrelevant information. A revised analysis of the data was provided in a report by the Netherlands Health Council (2004). With the cognitive function tests, only one statistically significant result was obtained in this reanalysis. UMTS exposure resulted in a higher completion rate of the memory comparison test in the control group without symptoms. This might be a coincidental impact. The findings in terms of symptoms have been explored in the subsection on electrosensitive persons.

The follow-up study by Regel et al. [19] solely evaluated the effect of the 2140 MHz UMTS BS-like RF signal (identical to that employed by [37]) on the well-being and cognitive functions in 33 EHS and 84 non-EHS subjects. Three experimental sessions were performed one week apart, with individuals randomly allocated to one of the six potential sequences of three exposure conditions, each lasting 45 minutes: 0 V/m (sham), 1 V/m (identical to that used by [37]), and 10 V/m (in order to assess any possible dose-response relationship). The study used a randomized crossover design and was double blinded. Cognitive performance was assessed using a SRT task, a 2-CRT task, the n-back task, and the visual selective attention task. The visual selective attention task was also used in [37]. There was no effect found from this study from any exposure level on the cognitive performance of the volunteers. Next, Elitti et al. [21] evaluated the influence of GSM and UMTS BS signals on the cognitive performance, focusing on attention and memory. They also utilized a variety of cognitive assessments. In addition to the control group of volunteers, this study included self-reported...
sensitive subjects. This is to test the hypothesis that the self-reported sensitive group would have decreased cognitive functioning. The subjects were exposed to Sham or GSM and UMTS signals from a BS antenna using a double-blind, counterbalanced, randomized cross-over approach. Both exposure signals have power flux densities of 10 mW/m² over the radiating region. The findings revealed that neither GSM nor UMTS BS signals had any significant influence on the attention or memory functions.

Wallace et al. [28] studied the effect of TETRA BS signal to two group of subjects (EHS = 48 and non-EHS = 132). The authors [28] also found that TETRA BS signal did not affect the cognitive performance for neither non-EHS nor EHS volunteers. Neither group were able to detect the presence of a TETRA signal at rates greater than chance (50%). It was also discovered that the EHS patients’ negative symptoms are caused by their fear of TETRA BSs rather than the low-level EMF exposure itself. In [22], Malek et al. also found no significant cognitive performance changes in both self-reported EHS and non-EHS groups when exposed to 2G and 3G MP BSs. In another recent study, van Moorselaar et al. [38] took a different approach in measuring the effects of RF-EMF exposure with personalized exposure setting at home involving 42 EHS subjects. A variety of RF-EMF types of exposure was emitted through their personal exposure units such as GSM 900, GSM 1800, cordless phone Digital European Cordless Telecommunications (DECT), UMTS and Wi-Fi 2.45 GHz signals. The authors concluded that during double-blinded testing, no participant was able to correctly identify when they were being exposed. This confirms the other findings that the RF-EMF exposure does not affect the symptoms reported by the EHS subjects. However, during follow-up sessions, EHS participants reported fewer symptoms compared to the symptoms reported before the exposure.

In a more recent study, Bogers et al. [23] observed the effects of continuous RF-EMF exposure from signals emulating GSM/UMTS BS, Wi-Fi and DECT. It was observed that Wi-Fi and GSM/UMTS BS exposures were associated with the self-declared symptoms by some of the EHS subjects. This finding contradicted against most of the findings from previous studies, which reported that there are no effects of RF-EMF exposure on the well-being of self-reported EHS individuals. Table 1 and 2 summarize the studies investigating the effects of RF-EMF exposure on cognitive performance, EMF perception and well-being of EHS subjects findings in literature.

V. WELL-BEING SUBJECTIVE SYMPTOMS

To further examine whether EMF exposure affects the behavior of human, many studies have investigated the second part of human behavioral traits, featuring well-being subjective symptoms. Exposure to diverse RF sources, both at home and at work, has been related to a wide spectrum of subjective symptoms. Headaches and migraines, tiredness, skin itch, and warm feelings are among the subjective symptoms reported by certain individuals and adolescents. Dizziness, blurred vision, memory loss, confusion and vagueness, toothaches, and nausea are some of the less often mentioned symptoms. These investigations are motivated predominantly by a small group of volunteers, who believed they are sensitive to EMF exposures (mobile phone or BS signal) and further perceived that they had suffered from health-related symptoms [19]–[21]. These studies have been very consistent in showing that there are no significant effects of exposure from these sources on this group’s well-being.

The first research related to BS exposure was from of Zwamborn et al. [37]. They investigated the effects of GSM and UMTS signal exposure on cognitive functions (discussed in the preceding subsection) and self-reported well-being (reported here) on volunteers who had previously reported symptoms attributed to GSM radiation and a control group without such symptoms. Both research groups observed a slight but substantial drop in well-being after being exposed to UMTS. No effects were seen when using GSM signals either at 900 or 1800 MHz. Next, a follow-up study by Regel [19] using an improved protocol investigated the effect only of the 2140 MHz UMTS BS-like RF signal on greater numbers of volunteers, identical to that used by Zwamborn et al. [37]. The cognitive performance (reported in the previous subsection) and well-being were investigated for 33 self-proclaimed RF-sensitive subjects and in 84 non-sensitive subjects. Although RF-sensitive subjects generally reported more health problems, in terms of the applied field conditions, Regel et al. [19] observed no difference between the two groups. Subjects were similarly unable to distinguish between exposure levels, but when they suspected exposure, they reported greater health problems, suggesting that psychological aspects may be implicated in this condition.

Oftedal et al. [25] investigated the effect of 902 MHz mobile phone signals on 17 volunteers (five women and 12 men) who have reported to develop symptoms analogous to those reported when MPs were used in the open provocation test. During the open provocation, both the volunteers and experimenters knew when the BS was “on” and “off” and, if it was “on”, it emitted GSM signal. Subjective symptoms were assessed in a double-blind randomized counterbalanced and crossover design for all volunteers. It was found that there was no evidence that MP exposure resulted in head pain or other health symptoms. More importantly, this study discovered that the subjects were unable to distinguish between non-exposure (Sham) and active exposure conditions, implying that a nocebo effect (negative expectation) may affect reported symptoms. Cinel et al. [39] used a larger number of participants in a double-blind, counterbalanced, randomized, and crossover design to prolong the patients’ symptoms linked to GSM MP exposure. A total of 496 volunteers (330 women and 166 men), who had not claimed to have health symptoms due to RF exposure, were divided into three groups and exposed to Sham and actual RF signals. Although one group exhibited an induced dizziness during GSM exposure, they found no consistency in
TABLE 1. Studies on the effects of EMF exposure on the cognitive performance.

| Study                         | Exposure Type               | Design                  | Subject                                    | Exclusion Criteria                                                                 | No and period of exposure assessments | Exp. time (min) | Exposure Setup                                      | SAR | Crossover | Room | Measurements |
|-------------------------------|-----------------------------|-------------------------|--------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------|----------------|-----------------------------------------------|-----|-----------|------|-------------|
| Kovisto et al. (2000)         | 902 MHz; 50 min L           | Single-blind, counter-balanced, pseudorandom | Healthy subjects: 24M, 24F (age range 18-34, mean age 23.2 years) | No neurological diseases                                                            | Single session                       | 30             | GSM MP mounted on the subject's head; antenna positioned on left ear with 4 cm apart from antenna | NR  | -         | ON, OFF | n-back (0-3) |
| Kovisto et al. (2000)         | 902 MHz; 60 min R           | Single-blind, counter-balanced, randomized | Healthy subjects: 24M, 24F (age range 18-49, mean age 26 years) | NR                                                                              | 2 sessions with 1 day interval          | 60             | GSM MP mounted on the subject's head; antenna positioned on left ear with 4 cm apart from antenna | NR  | -         | ON, OFF |                   |
| Carpio et al. (2004)          | MP GSM 982.46 MHz; 45 min l, peak power of 2 W, equivalent to an average power of 0.25 W | Double-blind, counter-balanced | Healthy subjects: 10M, 10F (age range 22-53 years, mean age 26.4 ± 2.86 years) | No MP; No neurological and psychiatric history; No medication; No sleep complaints | 3 sessions with interval of 48h between session | 45             | Helmet (antenna oriented to temporoparietal areas and microphone oriented towards the mouth, 1.5 cm from the left ear, 28° MP (0°) on the right side of the head, only helmet ON/OFF; helmet and MP | Max | 6.5 W/kg  | BSL, ON, OFF | SRT, CRT, VS, SUB |
| Regel et al. (2006)           | BS UMTS 2140; 45 min, 2 m   | Double-blind, randomized | Healthy subjects: 33 EHS (14M, 19F); 84 control (41M, 43F) (age range 20-60 years, mean ± SD = 37.7 ± 10.93, IMS 39-50 kg/m²) | No pacemakers, cardiac pacemaker, artificial cecchus, drugs; No smoking; No chronic diseases; No pregnancy; No head injuries; neurology; No systemic diseases; No sleep disturbances (average alcohol consumption) | 3 experimental sessions; 1 week of scheduled at the same time of day (~1 h) | 45             | The antenna at 1.5 m height and 2 m distance from the subject, targeting the left side of the body from behind, with a field incidence angle of 25° with respect to the coraco-acetabular plate | -  | 0 V/m, 1 V/m, or 10 V/m | (0, 1, 10 V/m) | One-side open chamber shielded with RF radiation absorbers |
| Carpio et al. (2008)          | MP GSM 902.4 MHz; 45 min L, peak power of 2 W, equivalent to an average power of 0.25 W | Double-blind, counter-balanced | Healthy subjects: 12F; 12M (age range 15-55, mean age 28/174.78 years) | No regular sleep cycle; No coffee; No alcohol; No MP | Weekly interval, 2 sessions scheduled at 9.00 am and 11.30 am | 45             | Helmet (antennas oriented to temporoparietal areas and microphone oriented towards the mouth, 1.5 cm from the left ear, 28° MP (0°) on the right side of the head) | Max | 0.5 W/kg  | ON, OFF | (ON, OFF) x (11, 15, 30, 45 min) |
| Candel et al. (2008)          | GSM 888 MHz and 2.4 GHz; EXP 1: 1.45 min L/R; EXP 2: 2.40 min L/R | Double-blind, randomized, counter-balanced | EXP 1: Healthy subjects: 116F; 64M (age range 22.2 years); EXP 2: Healthy subjects: 112F; 52M (age range 18-42 years, mean age 23 ± 5 years) | No MP for at least 1 h before each session | EXP 1: 45 sessions; EXP 2: 2 sessions | 45             | MP was fixed on a "cage/cap" that was mounted on the head | Max | 1.4 W/kg  | ON, OFF | Exp 1: n-back (2-3), VIG; Exp 2: Strobe, VS, Strobilin |
| Eltiti et al. (2009)          | BS; GSM 900 = 1800; UMTS 2020; 50 min, 5 m | Double-blind; counter-balanced, randomized | 44 EHS (mean age 46.1 years, SD 13.2); 44 control (mean age 47.0 years, SD 12.6) | No brain injury; No epilepsy or cerebrovascular event; No medication in 4 months prior to testing | 4 sessions, weekly interval at approximately the same time of day (~3 h) | 50             | GSM signal (combining both 900 and 1800 MHz) and UMTS signal (2020 MHz) over the area where the participant was seated | -  | 10 mW/m² | GSM, UMTS, OFF | DIS, DS, mental arithmetic |
| Malt et al. (2012)            | BS; GSM 945 MHz; 1.840 MHz; UMTS 2140 MHz; 2 m | Single-blind, counter-balanced, randomized | 100 EHS, 100 non-EHS | No sleep interference | 4 sessions | 50             | BS antenna (Kathrin 8001016380/GSM900/GSM 1800/UMTS) is placed at 1.5 m from the ground and 2 m in distance from the subjects | -  | 1 V/m  | GSM, UMTS, OFF | RF shielded room, lined using microware absorbing sheets |

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TABLE 1. (Continued.) Studies on the effects of EMF exposure on the cognitive performance.

| Sauer et al. (2015) [29] | TETRA hand-held transmitter 385 MHz: 2 h/6 min L | Double-blind, randomized | Healthy subjets: 20M (age range 20–35 years, mean ±SD: 25.4±6.2 years) | No sleep disturbance | Non-smokers | No drugs or medication | No implantations or tattoos on head | Intervals of 2 weeks, 9 daytime assessment in the afternoon at a fixed time frame | 150 s/day | Customized light weight condition on the left side of their heads | (1) TETRA low level (max SAR: 1g-1.5 W/kg) | TETRA high level (max SAR: 1g-6 W/kg) | Shielded with low background field | Test for Attentional Performance (Divided attention, VIG), Visual Test system (Detective attention) and n-back (0.3) (Working memory) |
|-------------------------|--------------------------------------------------|--------------------------|-----------------------------------------------------------------|------------------|-------------|---------------------|--------------------------|--------------------------------|-------------------|---------------------------------|-----------------|-----------------|--------------|-------------------------------|
|                         | Double-blind, counter-balanced, randomized       | UMTS: Healthy subjects 20F (aged 20 ± 3 years) | LTE: 13F 13M (aged 21 ± 3 years) | No smoking | No alcohol | No coffee | Moderate MP use | 2 sessions with 1 week interval between session at 8 am - 6 pm | 20 | Patch antenna moved in a position mimicking the normal use of an MP: the center of the patch antenna was near the exit of the ear canal, above the ears, at a distance of 7 cm | 1.8 W/kg | (UMTS) S/L OFF | Dimly lit room | Stroop test (executive function, processing speed, selective attention) | Note |

BSL = Baseline, CRT = Choice Reaction Time, DISS = Digit Symbol Subtration Task, DS = Digital Staircase, EXP = Experiment, F = Females, M = Males, NR = Not Reported, POST = Post Exposure, R = Right, SD = Standard Deviation, SRT = Simple Reaction Time, SUB = Subtraction Time, VER = Verification Time, VIG = Vigilance, VS = Visual Search, ↑ = increased, ↓ = decreased.

VI. PHYSIOLOGICAL PARAMETERS (HEART RATE, BLOOD PRESSURE AND BODY TEMPERATURE)

Few studies have validated that MP [24]–[27] and BS exposures [10], [20]–[22], [28] did not induce physiological effects (variation in blood pressure and heart rate). When both self-reported EHS and non-EHS groups were exposed to 3G Wideband Code Division Multiple Access (WCDMA) MP in [26], Kwon et al. discovered there is no significant physiological changes (heart rate, heart rate variability, and respiration rate). Moreover, WCDMA was found to not affect the heart rate, respiration rate, heart rate variability, or subjective symptoms in adults, according to Choi et al. [27]. Besides that, Malek et al. [22] also reported that BS transmissions had no significant short-term impacts on heart rate, blood pressure, or body temperature. Next, Andrianome et al. [10] observed the effects of continuous RF-EMF exposure from signals emulating GSM 900, GSM 1800, DECT and 2.45 GHz Wi-Fi signals. Similarly, it was discovered that these signals had no effect on the EHS participants’ autonomic nervous system, which included blood pressure and heart rate variability. Most recently, Masrakin et al. [40] observed that wearing textile antennas emitting 2.45 GHz signals also had no effect on adults’ blood pressure, heart rate, or body temperature. Table 2 presents the physiological parameters, EMF perception and well-being findings in the literature.

VII. EEG

Electrophysiological studies have indicated that a person’s waking or resting EEG is affected by GSM MP [36],[41]–[46]. These findings consistently indicated that there were increases of alpha rhythms (~8-12 Hz) with this exposure. Other studies show a decrease [47] and no effect [48], [49] of MP exposure on the waking EEG. Researchers in [41] investigated the effect of exposure to a GSM 900 signal on EEG waking activity and its temporal development in double-blind, cross-over design tests. The experimental procedure of this study is similar with the one reported in [34]. A total of 20 volunteers were assigned randomly to two groups, and one group was exposed for 45 minutes before the session, and the second group was exposed for 45 minutes during the session. The results demonstrated an increase of alpha power, and this finding was confirmed later when the study was replicated with a substantial sample size (N = 120) [41]. Further, Croft et al. [43] extended this study by examining three distinct age groups with mobile phone exposure operating using both GSM and UMTS technologies, involving 41 adolescents, 42 adults, and 20 elderly people in a double-blind, crossover counterbalanced design. Only the adults had increased alpha rhythms during the GSM exposure, which was consistent with the findings from [41]. However, this study failed to replicate this effect for adolescents and elderly people. Vecchio et al. [45] also examined the eyes-closed resting EEG in alpha rhythms, and found that they are affected by GSM radiation in inter-hemispheric functional coupling. Their results have also showed a positive correlation between the subject’s age and the inter-hemispheric frontal alpha coherence. The possibility of the increase of the alpha rhythms might be due to hyper-excitability that aggravated an age-related physiological reduction of the cholinergic tone (an organic molecule that functions as a neurotransmitter in the brain). Next, Roggeveen et al. [46] found an increase in alpha, slow beta, fast beta, and gamma bands on adult’s EEG exposed to a short-term 3G dialing mobile phone. The 3G mobile phone was dialled from a fixed line in another room during the exposure conditions. In contrast, Perentos et al. [47] found a reduction in alpha power on adult’s waking EEG exposed to pulse-modulated GSM mobile phone, which contradicted the previous findings. The main limitation of this study was that a single-session protocol was used instead of four different
| Study | Exposure Type | Design | Subject | Exclusion Criteria | No and period of exposure measurements | Exposure time (min) | Exposure Setup | SAR | E-field strength/Power density | Crossover | Room | Measurements | Results |
|-------|---------------|--------|---------|-------------------|----------------------------------------|---------------------|-----------------|-----|-----------------------------|----------|------|----------------|--------|
| Thavenet al. et al. (2004) [24] | MP, GSM 960 and 1800 MHz, 35 min | Double-blind, randomized, placebo-controlled | Healthy subjects, mean age 30.8 years, SD 6.8 years, BMI 23.3 (22.2-25.3) kg/m² | NR | 2 sessions, weekly interval at 1 pm - 5 pm | 65 | Dual band MP and a physically identical but inactive MP were located on a plastic bed helmet. RF field recording antenna placed around 20 cm from the active MP | 900 MHz: 1.58 W/kg | - | [GSM 900, GSM 1800, GPP] | EMF shielded laboratory | Physiological parameters (BP and HR) | No effect on BP and HR |
| Regel et al. (2006) [19] | BS UMTS 2140 MHz, 45 min, 2 m | Double-blind, randomized | Healthy adults, mean age 26-60 years, BMI 19-30 kg/m² | No pacemakers, hearing aids, artificial cochlea, drugs/No smoking/No chronic/No pregnancy/No head injuries/No sleep disturbances/Average alcohol: No shift workers-No long-haul flights (>7 h time zone difference) within the last month | 3 experimental sessions at 1-week intervals scheduled at the same time of day (<±2 h) | 45 | The antenna at 1.5 m height and 2 m distance from the subject, targeting the left side of the body from behind, with a field incidence angle of 25° with respect to the horizontal vertical plane | - | - | - | - | 5 subjective well-being symptoms | No effect on subjective symptoms |
| Oehde al. et al. (2007) [25] | MP, GSM 962.4 MHz, 30 min | Double-blind, randomized, sham-controlled | Healthy subjects, mean age 30.8 years, BMI 23.3 (22.2-25.3) kg/m² | No MP | Max takes 4 sessions, ≤5 days intervals between sessions | 30 | Antennas mounted symmetrically at the sides of the subject's head. Wooden bars restricted the sideways movements of the head. Antenna positioned 8.1 cm from the head | Spatial peak SARa | - | (ON, OFF) | Control room next to the shielded exposure room | 4 subjective well-being symptoms (Physiological parameters (BP and HR) | No effect on subjective symptoms |
| Citelli et al. et al. (2004) [30] | GSM 888 MHz and CW, Exp 1: 43 min LR, Exp 2: 240 min LR | Double-blind, counter-balanced | EXP 1: Healthy adults, mean age 30.8 years, BMI 23.3 (22.2-25.3) kg/m² | No MP | Weekly interval, conducted 2 sessions | 40 | MP attached to a cap that was then positioned on participant's head | Spatial peak SARb | - | (ON, OFF) | - | 5 subjective well-being symptoms | No constraint on subjective symptoms |
| Ettel et al. (2007) [20] | BS, GSM 960 + 1800 MHz, UMTS 2020, 16 min, 5 m | Double-blind, counter-balanced, randomized | EXP 14: Healthy subjects, mean age 30.8 years, BMI 23.3 (22.2-25.3) kg/m² | No brain injury | 4 sessions, No pacemaker or/and weekly | 50 | GSM signal (combining both 900 and 1800 MHz) and UMTS signal (2020 MHz) over the area where the participant was seated | Spatial peak SARb | - | (ON, OFF) | - | 6 VAS subjective well-being symptoms, 57 EHS symptoms, 57 EHS symptoms, Physiological parameters (BP and HR) | No effect on subjective symptoms, EHS symptoms, BP, HR |
| Wallace et al. (2016) [28] | BS TETRA 420 MHz, 50 min, 3 m | Double-blind, counter-balanced | EXP 15: Healthy subjects, mean age 30.8 years, BMI 23.3 (22.2-25.3) kg/m² | No brain injury, no memory loss, no headache | 3 sessions, interval at the same time of day (<±2 h) | 50 | Participants seated 4.95 m from antenna of the BS and used TETRA signal release 1 (frequency, 390-392 MHz) Telecommunications Standards Institute (UTSI) | Spatial peak SARb | - | (ON, OFF) | - | 6 VAS subjective well-being symptoms, 57 EHS symptoms, Physiological parameters (BP and HR) | No effect on subjective symptoms, EHS symptoms, BP, HR |
| Kwon et al. (2012) [36] | 3G WCDMA 1950-2440 MHz, 64 min | Double-blind, counter-balanced, randomized | EXP 17: Healthy subjects, mean age 30.8 years, BMI 23.3 (22.2-25.3) kg/m² | No caffeine/No smoking/No exercise, enough sleep | 2 sessions, 11-10 interval between sessions | 64 | Dummy MP containing a WCDMA modulated within a headrest placed on the head | Spatial peak SARb | - | (ON, OFF) | - | 8 subjective well-being symptoms (Physiological parameter (HR)) | No effect on subjective symptoms and HR for
| Study | Region | Frequency | Study Details | EMF Sources | Duration | No. of Subjects | Main Findings |
|-------|--------|-----------|---------------|-------------|----------|----------------|---------------|
| Choi et al. (2014) | MP | 3G WCDMA, 1800 MHz, UMTS 2100 MHz | 26 adults, double-blind, randomized | No caffeine/ No alcohol/ No smoking | 2 sessions/ 1-10 days interval between sessions | Dummy MP containing a WCDMA module within a booted plastic placed on the bed | 1.57 W/kg | 6.9 V/m (ON, OFF) | Laboratory subjective well-being symptoms, Physiological parameter (HR), No effect on subjective symptoms and HR |
| Malik et al. (2013) | BS | GSM 900 MHz, UMTS 1900 MHz | Single-blind, counter-balanced, randomized | No shift worker | 4 sessions | BS antenna (Katharina 800 MHz GSM/900 MHz UMTS) is placed at 1.5 m from the ground floor and at 2 m from the subjects | - | 1 V/m (GSM 900 MHz, UMTS, OFF) | RF shielded room, blind using microwave absorbing sheets | No effect on physiological parameters (BT, BP and HR) |
| Anderstamne et al. (2017) | BS | GSM 900 MHz, GSM 1800 MHz, UMTS, DCS/1800, WCDMA 4.25 GHz | Double-blind, counter-balanced | No alcohol/ No caffeine for 24 hours prior to and during the study | 2 sessions/ 1 week | No external EMF sources were allowed and the exposure consisted of a series of EMF signals emitted from a generator and a horn antenna | - | 1 V/m (GSM 900 MHz, UMTS, OFF) | SPD chamber | No effect on physiological BP and HRV |
| van Moorrees et al. (2017) | BS | GSM 900 MHz, GSM 1800 MHz, UMTS, DCS/1800, WCDMA 4.25 GHz | Double-blind, randomized, controlled | | | | | 150 | Max. 6 V/m (average exposure levels at the upper body) | (GSM 900 MHz, UMTS, DCS/1800, WCDMA) | Home and another location where they felt comfortable | EMF Perception, Symptoms | No effect on EMF perception but have effects on EHS symptoms |
| Roger et al. (2018) | BS | GSM 900 MHz, GSM 1800 MHz, UMTS, DCS/1800, WCDMA 4.25 GHz | NR | | | | | | (GSM 900 MHz, UMTS, DCS/1800, WCDMA) | At home inside, at home outside, at work or educational institution, elsewhere, travelling | EMF Perception, EHS subjective symptoms | Have effects on EHS symptoms |
| Marmkin et al. (2019) | MS | Wearable textile antennas 2.45 GHz | Single-blind, counter-balanced, randomized | No artificial clothing, headsets, pacemakers/ No smoking/ No alcohol/ No caffeine/ No use of antihypertensive drugs: No psychiatric disease/ No drug in the previous 6 months/ No long-haul flight for >5 h of different time zones/ No shift worker/ Matched menstrual cycle | 2 sessions | Mounted TX on the upper right arm. Both the TX and Rx antennas were both vertically oriented (with the smaller placed on the top section) when mounted on the subject’s body. Rx was mounted on the left chest of the subjects | For 10g SAR TM: 2.85 W/kg | 10g SAR: 2.35 W/kg | (ON, OFF) | RF-shielded room | 10 subjective well-being symptoms, Physiological parameters (BT, BP and HR) | No effect on subjective symptoms and physiological parameters (BT, BP and HR) |

**Notes:** 20 control 13M BF (mean=2 9.4, SD=5.5); 26 men 13M BF (mean=2 8.4, SD=5.5); 26 women 13M BF (mean=2 5.3, SD=0.7).
### TABLE 3. Studies on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed.

| Study          | Exposure Type          | Design                        | Subject                      | Exclusion Criteria                                                                 | No and period of exposure assessments | Exposure time (min) | Exposure Setup                                                                                           | SAR  | E-field strength/ Power density | Crossover | Room                        | Measurements | Results                  |
|---------------|------------------------|-------------------------------|------------------------------|----------------------------------------------------------------------------------|----------------------------------------|---------------------|----------------------------------------------------------------------------------------------------------|------|-----------------------------|------------|-----------------------------|--------------|-----------------------------|-----------------|--------------------------|
| Huber et al.  | Pulse-modulated GSM 900; 30 min; L | Double-blind                 | Healthy subjects: 16M (age range 30-35 years; mean age in (PET) study 22.5 years; in sleep study 22.3 years) | No caffeine/No alcohol/No medication/Maintain regular sleep/wake schedule/No MP/No subjects with sleep apnea, nocturnal myoclonus and low sleep efficiency | 2 sessions ≤5-week intervals between exposures | 30                  | Subjects sat on a chair with their heads positioned between two plates to ensure a well-defined location with respect to the two planar antennas | 0.5 W/kg | (OFF) | Sleep laboratory | 10 min eyes closed | 9-11 HI* | (During)                  |
| Curtius et al. | GSM 902.40; 45 min L    | Double-blind                 | Healthy subjects: 10M 10F (mean age 26.4 ±2.86 years, range 22-33 years) | No psychological, neurological condition, antisocial behavior/No history of antisocial behavior/No history of head injury/No extended period of unconsciousness/Normal hearing and normal (or accompanied to-normal) vision | 3 sessions | 45                  | A GSM MP set via laptop and manufacturer software to continuously transmit a 405 MHz digital signal | Without EEG apparatus: 0.64 W/kg | (OFF) | (BUS, OFF) | NR                  | 7 min eyes closed | 9-10 HI* | (During)                  |
| Curtius et al. | GSM 895; 30 min L/R    | Double-blind, counterbalanced, randomized | Healthy subjects: 6M 7F (mean age 31.3 ±13 years, range 18-49 years) | No smokers/No noise problems/No psychiatric medication/No history of psychiatric disorder/No history of head injury/No caffeinated beverages and alcohol for 24 h prior to testing | 2 sessions with 1 week interval | 30                  | Cradle containing a 2G handset placed on one side of the head and a 3G handset on the other side, with neither MP transmission | 20 (900MHz): SAR 0.7 W/kg, max peak spatial: (10g) = 0.78 W/kg | (OFF) | (DURING, POST) | NR                  | 10 min eyes open (during); 10 min eyes open (post) | 9-12 HI* | (During)                  |
| Vocchio et al. | GSM 902.49; 45 min L    | Double-blind                 | Elderly (11F 5M; age range 60-75 years) | No caffeine/No alcohol/No regular sleep habits/No MP/Postmenopausal | 3 sessions on separate days | 50                  | Helmet holding two MPs, MPs were oriented in the normal position. In one session the signal was turned on for 45 min (GSM), in the other one it was turned off. | 20 (900MHz): SAR 0.7 W/kg, max peak spatial: (10g) = 0.78 W/kg | (ON, OFF) | (PRE, DURING, POST) | Sound attenuated and metal-shielded recording room | 10 min eyes open (during); 5 min eyes open (after cognitive test 1); 5 min eyes open (after cognitive test 2); 5 min eyes open (post) | 9-12 HI* | (During)                  |
| Peronatis et al. | GSM 900; 20 min R  | Double-blind, counterbalanced, randomized | Young adults: 20M 12F (mean age 24.5 years, SD ±5 years) | No alcohol/No MP/No caffeine consumption within the 6 h prior to the experiment | 4 sessions | 20                  | MP placed according to the standard ear-to-ear position, over the right hemisphere. The speaker and antennas located over the auditory cortex. MP to place with a specially configured holder. Patch antenna placed next to the right ear | 10 g peak spatial: SAR level of 1.95 W/kg | (OFF) | (OFF, POST) | Diedly lit room | 5 min eyes closed (before); 5 min eyes closed (during) | 9-12 HI* | (During)                  |
| Trzaskowski et al. | 5G UMTS 1947 MHz; 30 min  | Double-blind                 | Healthy subjects: 8M 9F (mean age 21.7 ±5 years; ±1.83; 1.0M 2F (mean age 24.0 days ±6.58 years) | No alcohol/No MP/No caffeine consumption within the 6 h prior to the experiment | 2 sessions | 30                  | Electro magnetically metal-shielded | (CW RF, PULSED RF, ELF, OFX) x (OFF, PRE, DURING, POST) | (OFF) | (PRE, POST) | Diedly lit room | 10 min eyes open (before); 10 min eyes open (during); 10 min eyes open (post) | None | (None) |                  |
| Loughman et al. | GSM 900; 30 min L     | Double-blind, counterbalanced | Healthy subjects: 12M 10F | No caffeine/Regular | 3 sessions at weekly intervals | 30                  | Two-planar antennas (left active only) on the participants head | (High SAR: 1.4 W/kg) | (HIGH SAR, NR, LOW SAR, OFF) | 3 min eyes open and 3 min eyes closed (before); 3 min eyes closed (after) | None | None |                  |
TABLE 3. (Continued.) Studies on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed.

| Study | EMF Source | Age Range | RF Exposure | EEG Conditions | EEG Parameters | Notes |
|-------|------------|-----------|-------------|----------------|----------------|-------|
| Roggeveld et al. (2013) | UMTS | 15 min | Single-blind, 30 min, balanced | No medical history of cardiac, nervous system disorders, smoking | Spectral power | EEG not affected by UMTS exposure. |
| Trunk et al. (2007) | UMTS | Young adults | Double-blind, randomized, 20 min | No alcohol use | Spectral power | No significant effect of UMTS EMF. |
| Vecsei et al. (2018) | UMTS | Adults | Double-blind, randomized, 20 min | No alcohol use | Spectral power | Alpha band decreased. |

In Figure 2 found that there is no indication of any negative impact of a short-term EMF-effect on cognitive function [17], [19], [21], [22], [29], [35], [36]. SRT, RT, VIG and SUB were decreased when the RF-EMF was off (RF-off) to on (RF-on), indicated by 15.4% from the findings in [32]–[34]. Meanwhile, the study with the least percentage (about 8%) in Figure 2 showed that the exposure by MPs on adults resulted in a reduction in CRT [34]. On the contrary, a rise in accuracy of VIG is reported in [33].

To further examine whether EMF exposure affects human behavior, studies and findings on the well-being subjective symptoms and physiological parameters are summarized in Figure 3. The effect of RF-EMF on the physiological parameters from the previous studies showed that the exposure of RF signal does not affect the volunteers’ heart rate (50%), blood pressure (39%) and body temperature (11%) [10], [20], [22], [24]–[28], [40]. Similarly, a majority (70%) of these studies...
FIGURE 3. Overview of the 13 selected studies which investigated the effects of EMF exposure with respect to physiological parameters (a) BP - Blood Pressure, BT - Body Temperature, EHS - Electromagnetic Hypersensitivity, and HR - Heart Rate and (b) well-being.

FIGURE 4. Overview of the ten selected studies which investigated on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed. $\alpha$ – Alpha wave, $\beta$ – Beta wave, and $\gamma$ - Gamma wave.

FIGURE 5. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the cognitive performance and their measurement results. CRT – Choice Reaction Times, EHS – Electromagnetic Hypersensitivity, RT – Reaction Times, SRT – Simple Reaction Times, SUB – Subtraction, and VIG – Vigilance.

FIGURE 6. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the physiological parameter (body temperature, heart rate and blood pressure) and their measurement results. BP – Blood Pressure, BT – Body Temperature, EHS – Electromagnetic hypersensitivity, and HR – Heart rate.

FIGURE 7. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the well-being subjective symptoms studies and their measurement results. EHS – Electromagnetic Hypersensitivity.

on well-being parameters reported that mobile phone and BS exposures did not induce subjective symptoms [19], [20], [25]–[28], [40]. However, minority of these studies (20%) found significant changes on subjective symptoms [23], [38] and indicated no consistent effects [39] when exposed to RF-EMF signal (10%).

Electrophysiological studies have revealed that a person’s waking or resting EEG is affected by exposure to RF signals from GSM mobile phone [41]–[47]. Based on Figure 4, the most significant observation is the increase in alpha rhythms ($\sim$8-12 Hz) [41]–[46] due to mobile phone exposure (50%). The increase of the alpha rhythms is interpreted as an altered cortical neuronal activity, probably mediated by changes in thalamic functioning [41], [44]. The smallest percentage (8.3%) from the overall studies indicated only effects of slow beta, fast beta, and gamma bands on adults’ EEG when exposed to a short-term 3G dialing mobile phone [46].
On the contrary, some authors found a reduction in alpha power on adult’s waking EEG exposed to pulse-modulated GSM [47], 3G and 4G [36] mobile phones.

The effects of RF-EMF radiation from mobile phones, BSs, and Wi-Fi on the human cognitive function, well-being health symptoms, physiological parameters (blood pressure, heart rate, and body temperature), and EEG is tabulated in Table 1, Table 2, Table 3. Their results are illustrated in Figure 2, 3, and 4, indicating inconsistency. Results of the exposure to the GSM900/GSM1800/UMTS/4G MPs, GSM900/GSM1800/UMTS BS, DECT and Wi-Fi are shown in in Figures 5, 6, 7 and 8. These research studies involved both EHS or non-EHS subjects evaluated in terms of cognitive performance, well-being, physiological and EEG parameters.

Based on Figure 5, most of the RF signals which affected the cognitive performance is 2G, followed by 3G signals. Most of these studies indicated that the signal transmitted has no effect on the subject’s intellectual performance. Researchers in [29] evaluated a TETRA hand-held transmitter with the longest duration of 2 hours and 30 minutes in the shielded room, whereas [36] performed the same investigation with at least 20 minutes of exposure. Both investigations validated that there are no changes/negative effects on their subjects’ cognitive ability. The results in [29] showed one effect on working memory (faster RT in 2-back task) that reflected an improvement in performance of cognitive function. However, results from [32]–[34] validated that there are changes in their cognitive performance, with decreased RT, SRT, CRT, SUB, VIG and increased VIG accuracy. The locations of these experiments are not mentioned, and this may potentially be a factor which influenced the findings. Figure 6 shows that most studies on physiological parameters, specifically for vital signs such as body temperature, heart rate, and blood pressure, showed no differences from previous studies. The number of studies conducted on EHS subjects is comparable to the number of studies conducted on non-EHS group. RF signal involving a lower frequency band (420 MHz) is presented only by [28] using TETRA BS, as depicted in Figure 7. It is evident from Figure 7 that majority of these research indicated that there is no impact on subjective symptoms. Most studies on the EEG pointed that α waves of the brainwaves increased, as shown in Figure 8.

In general, this analysis indicated that all previous research aimed to determine the effects of TETRA/2G/3G/4G/Wi-Fi/DECT on health-related parameters. None of them investigated the effects of the human exposure to 5G signals, both in the sub-6 GHz and millimeter wave bands (up to 30 GHz). Thus, further research into the effects of 5G on human health is clearly required, as most available studies on the cognitive performance, physiological parameters, and well-being of human are limited to the use of GSM900/GSM1800/UMTS/4G mobile phone, GSM900/GSM1800/UMTS base station, DECT and Wi-Fi signals. Moreover, the effects of 5G base station signals (centered at 700 MHz, 3.5 GHz, or 28 GHz) have
not considered. Most importantly, based on this exhaustive literature review, there are yet any published evaluations studying the effects of exposure from 5G base stations on the cognitive performance, well-being, and physiological parameters (heart rate, blood pressure, body temperature) in adults. Secondly, more than half of the studies in literature focused on the RF-EMF effects due to exposure from MPs, reporting a maximum average SAR of 1.95 kg/W [47]. This value does not exceed the current ICNIRP exposure guideline for the public, which is 2 W/kg near the human head. Meanwhile, the power densities used in all studies were limited to a maximum of 10 V/m. This value is also well below the ICNIRP limit for the public. Available studies also showed that higher SARs and E-field strengths did not induce any health effects (well-being, cognitive performance) and physiological parameters, neither when exposed to RF-EMF from MPs and BSs. However, when exposed to MPs (for 2G, 3G and 4G signals) with higher SAR values, EEG decrease is observed in [36], [47]. Despite that, there is again yet any study reporting the effects of BS signal exposure on the EEG of human.

Note that there exist several significant differences in terms of methodology and the protocols previous studies when examining the effects of RF-EMF exposure on the cognitive functions. The first key parameter is the dosimetry configuration. There are two types of exposure reviewed here: (i) MP/TETRA hand-held/wearable textile antenna and (ii) BS. Therefore, different dosimetry methods are needed according to the types of radiating devices. Power density and SAR are the two most widely accepted metrics to measure the intensity and effects of RF-EMF exposure [18]. For MP/TETRA hand-held and wearable antenna exposures, the dosimetry standard used is SAR due to the close proximity between such radiating structures and the human head/body, and is within the near-field region. Meanwhile, power density or E-field strength dosimetry is used to assess BS exposure, as they are in the users’ far-field region. SAR is defined as a measure of the power absorbed per unit of mass (human body tissue). It can be spatially averaged over the total mass of an exposed body or its parts, and is calculated from the root-mean-square electric field strength, $E$ defined in volts per meter (V/m), calculated as follows [40]:

$$\text{SAR} = \frac{\sigma \cdot E}{\rho} = \frac{c}{\rho} \frac{\partial T}{\partial t} \bigg|_{t \rightarrow 0^+}$$

The conductivity, $\sigma$ is defined in Siemens per meter; and the mass density, $\rho$ represents the biological tissue density in kilogram per cubic meter. SAR also describes the initial rate of temperature rise of a tissue, $\partial T/\partial t$ as a function of the specific heat capacity ($c$). The power density, $S$ is related to the electric field strength $E$ by the free space impedance $Z_0 = 120\pi\Omega$ according to the following expression [1]:

$$S = \frac{E^2}{Z_0} = \frac{E^2}{120\pi}$$

The studies in [32], [33] which found changes in the cognitive function of human upon exposure, however, did not report the SAR levels. On the other hand, other studies which reported SAR levels [17], [29], [35], [36] and E-field strength/power density [19], [21], [22] indicated that the exposures did not affect or show negative effects on the cognitive functions of the volunteers, as shown in Table 1. Note also that all studies reported SAR levels within the regulatory limits of either 2 W/kg for the human head, 4 W/kg for the human limb,

![proposed schematic diagram](image-url)
or E-field strength/power density within the limit of 61 V/m or 10 W/m² between 2 and 300 GHz, as specified by ICNIRP. Another key observation is that assessments of cognitive functions were performed in either unknown or varying room conditions. For instance, the experimental room conditions are not reported in [32]–[34]; whereas these studies reported variations in cognitive performance due to MP exposure. However, Curcio et al. [35] replicated the work in [34] by conducting the experiment in a shielded, soundproof, and temperature-controlled room to assess cognitive functions of volunteers. As a result, they observed that the MP exposure did not affect any cognitive functions. Similarly, other studies in [19], [21], [22], [29], [36] reported the room conditions but observed no effect or negative effect of MP and BS exposures on cognitive function. Conversely, the only study which reported no effect of MP exposure on the cognitive function did not clarify the room condition [17]. In short, the studies observing effects on the cognitive performance of volunteers have either not reported their SAR/ E-field strength/power density levels or the room conditions. The possible remedy to this is to characterize the impacts on cognitive performance solely due to the BS RF-EMF exposure in 5G sub-6 GHz or mmWave range in terms of E-field/power density dosimetry. Such exposure experiments also need to be performed in an RF-shielded room to minimize the interference from other EMF sources and the effects of variable room temperature and relative humidity, as these factors may considerably affect the outcomes [26]. In general, the presented studies mainly showed no indication of RF-EMF effects on the well-being subjective symptoms and physiological parameters. On the contrary, the significance of this exposure is rather unclear when the EEG was investigated, as there are contradictory findings. RF-EMF exposure is seen to affect EEG even when the experiments were performed in a controlled environment (inside the RF-shielded room).

IX. CONCLUSION
This work presents an analysis of exposure studies conducted using signals from 400 MHz to 1750 MHz (for 4G). From this analysis, the following conclusions are made:

- Most of the studies in literature using 2G/3G/4G showed no effects and no consistency in how exposure to these signals affected the cognitive, physiological parameters, well-being, and EEG of the volunteers.
- Most research on human cognition, physiological parameters, and well-being so far have focused on the impacts of GSM900/GSM1800/UMTS/4G MPs, GSM900/GSM1800/UMTS BSs, DECT, and Wi-Fi exposures.
- There is an absence of studies reporting the effects of 5G (700 MHz, 3.5 GHz, or 28 GHz) BS signals on adults in terms of cognitive performance, well-being, or physiological markers (heart rate, blood pressure, and body temperature).

Figure 9 and 10 illustrated the possible flowchart and schematic diagram to study the effects of 5G BS exposure signals for sub-6 GHz and mmWave bands (up to 30 GHz) to human subjects. Data from such a study will be useful in explicitly determining the significance signal exposure from 5G BS on human health, considering their much closer proximity to users.

ACKNOWLEDGMENT
Techнопreneur UniMAP Sdn Bhd is involved in the management of this project.

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TASNEEM SOFRI (Graduate Student Member, IEEE) received the bachelor’s degree (Hons.) in electronic engineering technology (electronic telecommunication design) from Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia, in 2020. She is currently pursuing the dual Ph.D. degree in communication engineering with the Faculty of Electronic Engineering Technology, UniMAP, and the University of Yamashita, Japan. Her research interests include electromagnetics applications specifically in bio-electromagnetics and machine learning optimization. She is a Student Member of the IEEE Malaysia Section.

HASLIZA A RAHIM (Senior Member, IEEE) received the bachelor’s degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA, in 2003, the master’s degree in electronics design system from Universiti Sains Malaysia, Pulau Pinang, Malaysia, in 2006, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, Perlis, Malaysia, in 2015. She was the Programme Chairperson of postgraduate studies at the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP). She is a Chartered Engineer, a Professional Technologist, a Research Fellow with the Advanced Communication Engineering Centre of Excellence (ACE), and the Head of the Bioelectromagnetics Group under ACE. In 2006, she joined the, SCCE, UniMAP, as a Lecturer, where she is currently an Associate Professor with the Faculty of Electronic Engineering Technology. She is also a Visiting Professor with Universitas Ubadiyah Indonesia and Daffodil International University. She was leading Malaysian Communications and Multimedia Commission Research Grant (worth U.S. $200 k). She has been mentoring several undergraduate and about 16 graduate students. She has authored and coauthored more than 160 leading international technical journals and peer-reviewed conference papers, including IEEE ACCESS, Sensors, Microwave and Optical Technology Letter (MOTL), Progress in Electromagnetics Research (PIER), and three articles in Nature Publishing Group journals (Scientific Reports), two patents granted, two patent filings, three copyrights, and five book chapters. Several research funds were granted nationally and internationally, such as Fundamental Research Grant Scheme, National Science Fund, and Short-Term Grant of UOWD (worth U.S. $425 k). Her research interests include wearable and conformal antennas, metamaterials, antenna interaction with human body, on-body communications, antenna and propagation, wireless body area networks, bioelectromagnetics, and wearable. She has been a member of the technical program committees of several IEEE conferences and a technical reviewer for several IEEE and other conferences. She is an Executive Committee of the Asia Pacific Women Inventors and Innovators Network (APWIIIN), a member of IEEE AP-S, and a Graduate Member of the Board of Engineers Malaysia. As an advisor, her supervised projects have also won prizes, such as the Third Place in the IEEE Malaysia Section Final Year Project Competition (Telecommunication Track), in 2017. She was awarded as the Chairman Discretionary Silver Award by the Global Women Engineers and Innovators Network (GlobalWIIN), in 2020. She received 36 medals and one Special Award (MIIA Leading Innovation Award Macau) at a number of high-profile international/national exhibitions, namely gold medal from the Kaohsiung International Invention and Design Expo (KIDE 2020), the Malaysia Technology Expo (MTE 2021), and i-PERLIS 2021. She was a recipient of the Best Paper Award from the 2020 International Conference on Broadband Communication, Wireless Sensors and Powering (BCWSP 2020), and the IEEE Malaysia AP/MTT/EMC Joint Chapter, in 2020 and 2021.

MOHAMEDFAREQ ABDULMALEK (Member, IEEE) is currently an Associate Professor with the Faculty of Engineering and Information Sciences, University of Wollongong in Dubai (UOWD), Dubai, United Arab Emirates. Before he joined UOWD, he worked as the Dean of the School of Electrical Systems Engineering, Universiti Malaysia Perlis. Prior to this, he held industry positions for five and half years with Alcatel and Siemens. At Alcatel, he worked at the Asia Pacific Regional Centre of Competence, specializing in mobile radio network design. At Siemens, he worked at the Information and Communication Mobile Division, where he developed the mobile strategy for the Malaysia market. He believes in hybrid, multi-disciplinary teamwork, and collaboration with researchers from other disciplines. He has obtained various national research and commercialization grants at the national levels. He has generated total research and development funds of USD 1.1 million over the past ten years, coordinated 28 research projects, funded 27 research assistants, and successfully graduated 25 Ph.D. and nine M.Sc. (by research) students. His product “Smart Communication Platforms at Low Altitude to Enhance Disaster Risk Management,” has been granted patent. To date, he has published 381 peer-reviewed scientific publications. His work has been cited more than 4,165 times and with an H-index of 30. His articles have attracted 215,630 number of reads in ResearchGate. He has written six books/book chapters. He maintains a broad range of research interests include applied electromagnetic, wearable textile antenna, microwave absorbers from agricultural wastes (rice husks, sugar cane bagasse, and banana leaves), effects of RF on health, RF energy harvesting, and wireless communication. His research outcomes have appeared in journals, such as Scientific Reports (Nature Publishing Group), IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, Progress in Electromagnetics Research, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, Journal of Electromagnetic Waves and Applications, Radioengineering, Mathematical Problems in Engineering, International Journal of Antennas and Propagation, IEEE ACCESS, and Journal of Measurement. His invention, “Design and Development of Frequency Selective Surface Structure to Enhance WLAN Application Signal,” won Bronze Medal at Seoul International Invention Festival, in 2014. He received special award from the World Invention Intellectual Property Associations (WIIPA). His inventions ‘Smart Material Antenna’ and ‘Smart antenna for unmanned aerial vehicle’ both won Silver Medal at Geneva Inventions, in 2012. He appeared in the World Health Organization list of experts in the world for RF, in 2014.

KHATIJA HHUSNA ABD RANI was born in Perak, Malaysia. She received the B.Sc. degree (Hons.) in statistics and the M.Sc. degree in applied statistics from Universiti Teknologi Mara, Malaysia, in 2011 and 2013, respectively. From 2014 to 2016, she joined the School of Electrical System Engineering, Universiti Malaysia Perlis, as a Lecturer. She is currently a Lecturer with the Institute of Engineering Mathematics, Faculty of Applied and Human Sciences, Universiti Malaysia Perlis. Her research interests include application of statistics in multivariate analysis and design of experiment.

MOHD HAFIZI OMAR received the M.S. degree in biomedical engineering from Universiti Teknologi Malaysia, Malaysia, in 2014. He is currently working as a Lecturer with the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis. He has published eight research papers in various international journals and conferences. His research interests include signal and image processing with application to biomedical data for automatic detection and prediction, control systems, and automation.
MOHD NAJIB MOHD YASIN (Member, IEEE) received the M.Eng. and Ph.D. degrees in electronic engineering from The University of Sheffield, Sheffield, U.K., in 2007 and 2013, respectively. Since 2013, he has been a Lecturer with the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis, Malaysia. His research interests include computational electromagnetics, conformal antennas, mutual coupling, wireless power transfer, array design, and dielectric resonator antennas.

MUZAMMIL JUSOH (Senior Member, IEEE) received the bachelor’s degree in electrical-electronics and telecommunication engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2006 and 2010, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013. He was an RF and Microwave Engineer with Telekom Malaysia Berhad (TM) Company, from 2006 to 2009, where he was also the Team Leader of the Specialized Network Services (SNS) Department based in TM Senai Johor. He is currently an Associate Professor. He is also a Principal Researcher with the Bioelectromagnetics Research Group (BioEM), Faculty of Electronic Engineering Technology, UniMAP. He is managing few grants under the Ministry of Higher Education Malaysia and applied Inspire Grant from UniMAP. He is also supervising a number of Ph.D. and M.Sc. students. He does preventive and corrective maintenance of ILS, NDB, DVOR, repeaters, microwave systems, VHF, and UHF based on contract wise Department of Civil Aviation (DCA), TUDM, PDRM, ATM, Tanjong Pelepas Port (PTP), MCMC, and JPS (Hidrologi Department). He holds an H-Index of 13 (SCOPUS). He has published over 156 technical articles in journals and proceedings, including IEEE Access, the IEEE Antenna and Wireless Propagation Letter (AWPL), Microwave and Optical Technology Letters (MOTL), the International Journal on Antennas and Propagation (IJAP), Progress in Electromagnetics Research (PIER), and Radioengineering journal and more than 80 conference papers. His research interests include antenna design, reconfigurable beam steering antennas, wearable antennas, MIMO, UWB, wireless on-body communications, in-body communications (implantable antenna), wireless power transfer, and RF and microwave communication systems. He is a member of the IET (MIET), the Antenna and Propagation Society (AP/MTT/EMC), and the Malaysia Chapter. He has received the Chartered Engineering Certification, in July 2017.

PING JACK SOH (Senior Member, IEEE) was born in Sabah, Malaysia. He received the bachelor’s and master’s degrees from Universiti Teknologi Malaysia, and the Ph.D. degree from KU Leuven, Belgium, in 2013. He is currently an Associate Professor with the Centre for Wireless Communications (CWC), University of Oulu, Finland. He started his career as a Test Engineer from 2002 to 2004, and an Research and Development Engineer from 2005 to 2006. He was then a Lecturer with Universiti Malaysia Perlis (UniMAP) from 2006 to 2009 before moving to KU Leuven as a Research Assistant from 2009 to 2013, a Postdoctoral Research Fellow from 2013 to 2014 and a Research Affiliate since 2014. He was then a Senior Lecturer from 2014 to 2017 and an Associate Professor in UniMAP till 2021. His research interests include wearable antennas, arrays, metasurfaces, on-body communication, electromagnetic safety and absorption, and wireless and radar techniques for healthcare applications. He was a recipient of the URSI Young Scientist Award, in 2015, the IEEE MTT-S Graduate Fellowship for Medical Applications, in 2013, and the IEEE AP-S Doctoral Research Award, in 2012. He was also the Second Place Winner of the IEEE Presidents’ Change the World Competition, in 2013. Three of his (co)authored journals were awarded the IEEE AP/MTT/EMC Malaysia Joint Chapter’s Publication Award, in 2020, 2019, and 2018, and another two journals were also awarded the CST University Publication Award, in 2011 and 2012. He is a Chartered Engineer registered with the U.K. Engineering Council and a member of the IET and URSI. He also volunteers in the IEEE MTT-S Education Committee.