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by Naren, A. Elhence, V. Chamola and M. Guizani
in IEEE Access, vol. 8, 2020, pp. 42980-43000

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SPECIAL SECTION ON ANTENNA AND PROPAGATION FOR 5G AND BEYOND

Received January 11, 2020, accepted January 21, 2020, date of publication February 27, 2020, date of current version March 12, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2976434

Electromagnetic Radiation Due to Cellular, Wi-Fi and Bluetooth Technologies: How Safe Are We?

NAREN[1], ANUBHAV ELHENCE[1], VINAY CHAMOLA[1], AND MOHSEN GUIZANI[2], (Fellow, IEEE)
[1]Department of EEE, Birla Institute of Technology and Science (BITS), Pilani 333031, India
[2]Department of Computer Science, Qatar University, Doha 2713, Qatar

Corresponding author: Mohsen Guizani (mguizani@ieee.org)

This work was supported by the Qatar National Research Fund (a member of The Qatar Foundation) under Grant NPRP10-1205-160012.

ABSTRACT The electromagnetic radiation (EMR) emitted out of wireless communication modules in various IoT devices (especially used for healthcare applications due to their close proximity to the body) have been identified by researchers as biologically hazardous to humans as well as other living beings. Different countries have different regulations to limit the radiation density levels caused by these devices. The radiation absorbed by an individual depends on various factors such as the device they use, the proximity of use, the type of antenna, the relative orientation of the antenna on the device, and many more. Several standards exist which have tried to quantify the radiation levels and come up with safe limits of EMR absorption to prevent human harm. In this work, we determine the radiation concern levels in several scenarios using a handheld radiation meter by correlating the findings with several international standards, which are determined based on thorough scientific evidence. This study also analyzes the EMR from common devices used in day to day life such as smartphones, laptops, Wi-Fi routers, hotspots, wireless earphones, smartwatches, Bluetooth speakers and other wireless accessories using a handheld radio frequency radiation measurement device. The procedure followed in this paper is so detailed that it can also be utilized by the general public as a tutorial to evaluate their own safety with respect to EMR exposure. We present a summary of the most prominent health hazards which have been known to occur due to EMR exposure. We also discuss some individual and collective human-centric protective and preventive measures that can be undertaken to reduce the risk of EMR absorption. This paper analyses radiation safety in pre-5G networks and uses the insight gained to raise valuable concerns regarding EMR safety in the upcoming 5G networks.

INDEX TERMS EMR, wireless, safety, standards, health, protection.

I. INTRODUCTION

The ever-increasing adoption of wireless communication has created a very complex situation of electromagnetic radiation (EMR) exposure. With new technologies such as 5G, the number of devices will increase exponentially and operate on a broader frequency spectrum. With this upcoming technology, the society will be more connected than ever before, and would witness huge economic growth. However, it is very important to identify beforehand, if any, harmful or adverse effects resulting from increased exposure of human beings.

Currently, there are about 15 billion wireless local area network (WLAN) devices ranging from Wi-Fi routers to Internet of Things (IoT) devices [1], 9 billion mobile connections, and about 67% of the world population currently uses mobile phones [2]. Any unidentified or unaddressed health hazard due to the use of these devices or exposure to their radiation could impact the health of people globally.

Several organizations at both national and international levels have established guidelines for limiting EMR exposure in residential as well as occupational scenarios. Scientific research on EMR exposure-related biological effects began as early as the 1940s [3], but gained significant pace in the early 2000s with the widespread increase of EMR exposure due to cellular communications.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has issued regulatory limits on EMR exposure for the general public and workers. ICNIRP's 1998 guidelines have been adopted by most of the countries in the world today [4]. But these limits only take into account the thermal effects of EMR and dismiss evidence on the biological effects of EMR exposure as unclear or

The associate editor coordinating the review of this manuscript and approving it for publication was Qammer Hussain Abbasi.

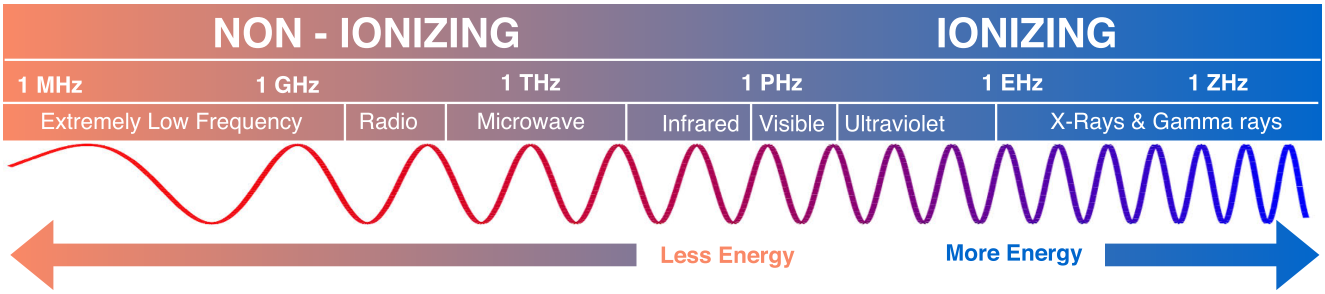


FIGURE 1. Ionizing and Non-ionizing radiation sources and there frequency bands.

unsatisfactory findings. In addition, there are several standards prescribed by medical bodies such as the Building Biology, BioInitiative, and Austrian Medical Association Standards. These limits have been arrived at after extensive scientific research of thermal, non-thermal, chronic exposure, and biological effects carried out by health experts from across the world. On comparing these limits with those prescribed by the ICNIRP, it can be seen that the limits prescribed by the medical bodies are several orders of magnitude lower than those prescribed by the ICNIRP. Therefore, a clear understanding of the differences between these limits, and an assessment of the current exposure levels in accordance with both kinds of exposure limits mentioned above is the need of the hour.

In the literature, many research studies have analyzed health hazards due to EMR exposure [5]. Numerous adverse health conditions such as cancer, infertility, damage to the auditory system, alteration of blood cells and blood flow, mental, cognitive and sleep disorders, and impaired childhood development have been identified in various studies. We have explored the literature in this area and presented a section describing various health risks associated with EMR exposure.

The major contributions of this paper are highlighted below.

- We analyse radiation levels of commonly used cellular, Bluetooth, and Wi-Fi devices to estimate how safe they are to human beings in terms of radiation.
- The procedure followed in this work serves as a tutorial for the general public who can arrive at a good estimate of their radiation exposure with minimal technical knowledge or expertise.
- We review several works which have identified various health hazards resulting from EMR exposure and presents the findings to highlight dangers of excessive EMR exposure.
- Then, we suggest techniques for people as well as societies/organizations to protect themselves from excessive EMR exposure and also presents ways to minimize ambient EMR levels in different environments like schools, hospitals, and homes.

The rest of this paper is organized as follows. In Section II, we discuss the nature of EMR used in wireless communication devices and the need to analyze EMR from various common sources such as mobile phones, laptops and other cellular, Wi-Fi, Bluetooth and IoT devices. In Section III, we discuss a few important standards and guidelines for EMR exposure which have been determined by scientific organizations/commissions to avoid EMR related health hazards in humans. In Section IV, we present our findings on the radiation levels present in common use cases of popular devices. In section V, we summarize the important health hazards of EMR exposure that have been documented and reported. In section VI, we describe some measures to protect ourselves from EMR and also discuss ways to minimize ambient EMR in public places. In section VII, we recommend some proactive prevention techniques which can be immediately adopted at both individual and societal levels to prevent harmful EMR exposure. In section VIII, we discuss our findings from section IV in light of sections II, III, V and VI. We finally conclude the paper in section IX.

II. PRELIMINARY BACKGROUND AND MOTIVATION

A. IONIZING AND NON IONIZING RADIATION

When referring to interaction of EMR with biological systems, EMR is categorized into two types: ionizing and non-ionizing. About 60% of the human body is water. Based on whether the incoming radiation is high enough to break the chemical bonds of water or not, it is categorized as ionizing radiation (if it can break the bonds) and as non-ionizing radiation (if it is not able to). Several classes of electromagnetic waves are classified as non-ionizing and ionizing radiation as depicted in Fig. 1. The frequencies we are interested in (radio frequencies) fall in the category of non-ionizing radiation. Some of the most common electronic/IoT devices which people use today such as mobile-phones, smartphones, laptops, wireless speakers and headphones, and smartwatches, all communicate using radio frequencies. Broadly, they can be categorized into devices which use cellular, Wi-Fi or Bluetooth technology as shown in Fig. 2. This kind of radiation has been linked with various adverse health effects in human beings. The severity of these effects varies with the power of radiation, distance of the radiation source, the kind of device, the type of antenna used in the device, the modulation technique used in the communication and the duration of exposure.

Electromagnetic radiation in the frequency range 20 KHz - 300 GHz is referred to as radio frequency (RF) radiation. Most of the commonly used communication services such as FM radio, television broadcast, satellite, cellular, Global

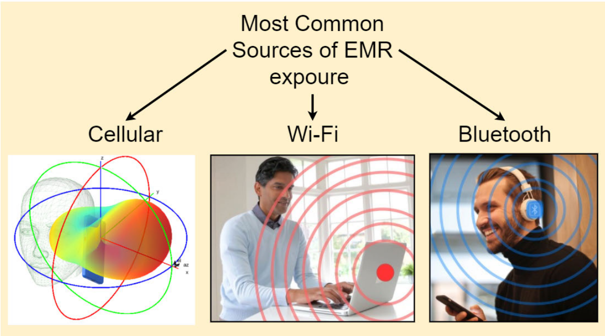


FIGURE 2. Most common sources of EMR exposure.

TABLE 1. Common wireless communication technologies.

Name of technology	Frequency	Deployment year
1G	800 MHz	1970-1980
2G 2.5G	850/900/1800/ 1900 MHz	1990 1985
3G	800/850/900/ 1800/1900/ 2100 MHz	2004
3.5G	1.8 GHz/2.6 GHz	2007
3.75G	3.5 GHz/5.8 GHz	2012
4G	1.8 GHz/2.6 GHz	2009
WIMAX	2.3 GHz, 2.5 GHz and 3.5 GHz	2008-2015
5G	600 MHz to 6 GHz and 24-86 GHz	2018
Wi-Fi	2.4/5 GHz	1997
Bluetooth (versions 1-5)	5 GHz	2000

Positioning System (GPS), Wi-Fi and Bluetooth all lie in this frequency range.

B. MOTIVATION

An antenna is a transducer which converts AC. electric currents flowing in metal conductors to radio frequency electromagnetic waves and vice-versa. Antennas are used in all wireless radio frequency communication devices. During transmission, AC. electric current is supplied to the antenna's terminals, which induces the antenna to radiate EMR waves in the radio frequency range. During reception, the antenna intercepts radio waves to generate an AC. electric current at its terminals, which is applied to a receiver before amplification. In the latest smartphones which are in use today, there are several antennas for different communication purposes such as cellular, GPS, Wi-Fi and Bluetooth. Table 1 lists the most commonly used wireless technologies at present and their frequency ranges. Fig. 3(a) shows the usage of multiple antennas in a smartphone. Similarly Fig. 3(b), Fig. 3(c) and Fig. 3(d) show the antennas used in the Jio-Fi 4G Hotspot, the Wi-Fi antennas present in a laptop, and the Bluetooth antenna used in a wireless earphone respectively.

A cell phone communicates wirelessly with a cellular base station that is typically hundreds of meters away. The antennas on a mobile phone are not directive, i.e, they transmit and receive EMR roughly in all directions. Their radiation pattern is roughly omni-directional. This enables good communication, because the user does not necessarily orient the phone in the direction of the cell tower. These antennas ensure the propagation of the electromagnetic waves to the, enabling communication. The omni-directional nature of these antennas can cause radiation energy to dissipate in all directions. But this means that a mobile phone emits radiation directly into the head of the user. Moreover, when the phone is situated in areas with weak reception such as the far end of its closest cell tower or in the basement of a building, its radiation increases by several magnitudes in order to ensure good connection with the cellular base station.

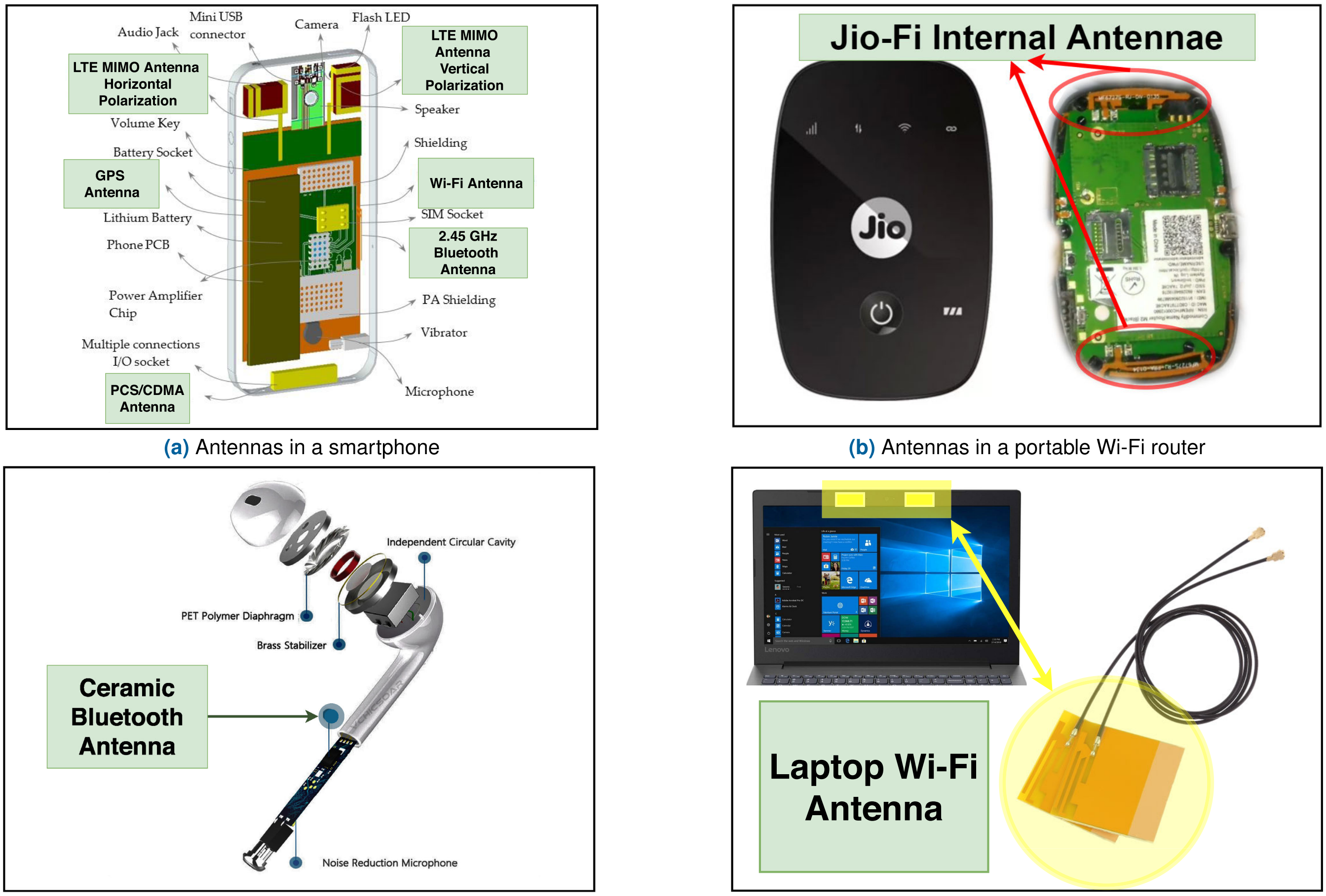
Laptops communicate with both Wi-Fi and Bluetooth technology, but Wi-Fi is used more extensively to connect to wireless routers located nearby. Just as for mobile-phones, the laptop antennas are designed to ensure good connection regardless of its orientation or position in a Wi-Fi zone. Hence, even laptop Wi-Fi antennas are roughly omnidirectional in nature. Laptops are mostly used either on the lap or on a desk. When used on the lap, severe amounts of radiation directly enter the legs, groin and torso region. Moreoever, since the antenna is located very close to the body, the magnitude of radiation is extremely high. When used on desks or tables, the face of the user directly faces the antenna. Most laptops have their antennas located at the top of the display. Laptops are used for several hours at a time in very close proximity and hence raise more concern than mobile phones which may be held next to the ears for just a few minutes during a call.

In the last few years, the popularity of Bluetooth headphones and earphones have increased drastically. Some of these earphones such as the one shown in Fig. 3(c) have the antenna extremely close to the ear. These devices are worn by users almost throughout the day and kept active almost continuously. In addition to the radiation from the earphone itself, the connected smartphone or mobile phone, kept in the pocket also emits Bluetooth radiation continuously.

For a common user, it is very difficult to measure the three-dimensional radiation pattern to estimate his own safety in regards to EMR exposure. Therefore, in this document we analyze the radiation levels from the most common sources to and scenarios of EMR exposure. We then correlate our findings with a few well-defined, scientifically and holistically determined safety limits.

III. STANDARDS AND GUIDELINES FOR ELECTRO-MAGNETIC RADIATION

Ideally, it is expected that a well defined, safe exposure limit would apply to people of all countries. But, there are striking differences that arise due to thermal effects, non-thermal



(a) Antennas in a smartphone

(b) Antennas in a portable Wi-Fi router

(c) Antennas in Bluetooth earphones

(d) Wi-Fi antennas in a laptop

FIGURE 3. Antennas in a smartphone.

health effects, and precautionary measures considered in determining the limits. Different countries across the world adopt different RF EMR exposure limits based on these considerations. For example, the United States adopts limits based only on thermal effects. Russia and China have taken non-thermal effects into account while determining their standards. Switzerland and Italy have taken precautionary measures to account for any adverse health effects which may be discovered in the future, and therefore adopt exposure limits even below non-thermal effects [6]. Damage arising from only tissue heating is considered while determining thermal exposure limits. Such safety limits are prepared based on the assumption that it is sufficient to consider only heating effects while trying to minimize harm to the human body. But in the last few decades, it has been well established that biological and adverse health effects occur at radiation levels which are too low to cause any heating, sometimes several hundred thousand times lower [7].

In this section, we discuss the guidelines on exposure limits prescribed by the ICNIRP, Building Biology, the Austrian Medical Association, and the BioInitiative. The ICNIRP guidelines is the most widely adopted guidelines in the world at present, being adopted by around 50 countries. But it only takes into account the thermal effects of EMR, while the standards prescribed by Building Biology, Austrian Medical Association, and the BioInitiative take into account thermal, non-thermal, chronic exposure, and biological effects of EMR as well. In this section, we present a comprehensive summary of the above-mentioned guidelines and standards in light of the requirement of this work, i.e., electromagnetic radiation due to cellular, Wi-Fi, and Bluetooth technologies.

A. ICNIRP

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is an international commission which specializes in non-ionizing radiation protection. The EMR exposure limits of more than 50 countries in the world today [8] are based on ICNIRP's 1998 publication [9]. This document provides different guidelines for occupationally exposed individuals and members of the general public. They have prescribed two types of restrictions, namely Basic Restrictions and Reference levels. Basic Restrictions are difficult to measure, especially for people who are not experts in the field of antennas and do not have access to sophisticated experimental setups. They require sophisticated experimental setups and costly equipment. But, Reference levels can be easily measured using simple handheld RF radiation meters. Here, we only consider the Reference levels for general public

TABLE 2. ICNIRP reference values for general public.

Name	Upper Band Frequency	Exposure Limit (in $\mu W/m^2$)
1G	800 MHz	4,000,000
2G	1900 MHz	9,500,000
3G	2100 MHz	10,000,000
4G	2.6 GHz	10,000,000
Wi-Fi	2.5 GHz	10,000,000
Bluetooth	5 GHz	10,000,000

exposure in the frequency ranges of the wireless technologies considered in this work. The Reference levels at these frequencies for general public exposure are listed below, where f is the frequency of the concerned EMR source. Table 2 lists the reference values (in $\mu W/m^2$) calculated for some wireless technologies.

400-2000 MHz : $f/200\ \mu W/m^2$
2-300 GHz : $10\ \mu W/m^2$

B. BUILDING BIOLOGY STANDARD

The Building Biology Standard [10] takes into account the physical, chemical and biological hazards present places where people work, live and sleep. It considers the influence of various factors such as different electric fields, magnetic fields, waves, radiation, indoor toxins, pollutants, fungi bacteria and allergens. Radio Frequency EMR is also included and addressed as a critical influence in their standard. It aims to enable an individual to identify, minimize and avoid all such factors in their own life without any need sophisticated equipment or scientific expertise.

Their evaluation guidelines are intended to be used in areas where there is risk of repeated long term-exposure such as sleeping and resting areas. Their guidelines are precautionary in nature and define four levels of concern which are listed below.

1) **Extreme Concern**: The values categorized under extreme concern require an immediate attention and swift correction. Short term exposures to radiation under this category will cause problems like headache, nausea, dizziness while long term exposures can lead to more serious diseases as discussed in section VI.
2) **Severe Concern**: The radiation values coming under this category are tagged as unacceptable from the point of view of building biology and they must be addressed. These values are unnatural for human beings. Chronic exposures to these radiation levels can sow the seeds of future health diseases.
3) **Slight Concern**: This is a precautionary category as radiation levels categorized under slight concern can affect sensitive population like pregnant women, small children and unhealthy people.
4) **No Concern**: This category ensures that the radiation levels are safe and will not cause any health hazard. The radiation levels in upper range of this category signify the background radiation level of our modern living environment which is inevitable in the current society.

In the case of RF EMR, the quantity to be measured is power density in the units of $\mu W/m^2$. Power densities (in $\mu W/m^2$) less than 0.1 indicate **no concern**, between 0.1 and 10 indicate **slight concern**, 10 - 1000 indicate **severe concern** and values greater than 1000 indicate **extreme concern**.

No concern : $\leq 1\mu W/m^2$
Slight concern : $1 - 10\mu W/m^2$
Severe concern : $10 - 1000\mu W/m^2$
Extreme concern : $\geq 1000\mu W/m^2$

According to the standard, the values mentioned above refer to peak measurements and are applicable to single RF sources such as GSM, UMTS, WiMAX, TETRA, Radio, Television, DECT cordless phone technology and WLAN except radar signals.

The standard treats pulsed or periodic signals (such as mobile phone technology, DECT, WLAN and digital broadcasting) as more critical sources and recommends that they should be assessed more seriously, especially in the higher concern ranges. Non pulsed and non periodic signals such as F.M, short, medium, long wave and analog broadcasting can be addressed more generously, especially in the lower concern ranges.

The exposure limits prescribed by the medical associations of many other countries are based on the Building Biology Standard. For example, the guidelines prescribed by the Austrian Medical Association (AMA) [11] suggest the same limits mentioned above as 'Within normal limits', 'Slightly above normal', 'Far above normal' and 'Very far above normal'.

C. BIOINITIATIVE STANDARDS

The BioInitiative report [11] is the work of renowned health professionals and many scientists on the potential hazards of exposure to EMR arising from the use of wireless technologies. The first edition of the BioInitiative report was released in 2007 and then updated in 2012. This report includes an extensive documentation of adverse biological health effects on both general and sensitive populations because of exposure to EMR. Their focus is primarily on chronic exposure to low frequency, extremely low frequency and radiofrequency EMR fields. BioInitiative claims to be an independent body, comprising of medically acclaimed professionals who believe that deployment of wireless technology always happens before the health risks are assessed. This report urges the necessity to reconsider the current situation regarding excessive use of wireless communication technology.

The following is a summary of the latest BioInitiative standards. The standard justifies the cumulative outdoor RF EMR limit to be reduced from 1000 $\mu W/m^2$ to just a few $\mu W/m^2$. Based on several studies related to health effects caused by mobile phone and base station radiation, the benchmark for 'lowest observed effect level' was found to be 30 $\mu W/m^2$. Considering the higher electrosensitivity of children, and a safeguard for chronic and long term exposures, the above mentioned value of 30 $\mu W/m^2$ is reduced by 10 times to set the *precautionary action level for chronic exposure to pulsed RF Radiation* between 3 and 6 $\mu W/m^2$. The BioInitiative report also states that this level is not definite, i.e., based on information from newer studies, it may decrease or increase this level.

IV. RESULTS

With the advent of technology, there are more wireless devices today than ever before, such as LTE phones, 3G phones, GSM and CDMA phones, wireless speakers, smartwatches, wireless earphones, portable Wi-Fi routers, wireless mice and keyboards, voice-controlled smart speakers like Alexa, health monitoring devices, etc. In places such as universities, offices and homes, multiple devices are communicating using different technologies at a given time. Note that a majority of devices communicate either using Wi-Fi, Bluetooth or cellular technology. Therefore we have investigated the power flux densities (PFD) of the EMR emitted from specific devices which are used very extensively in our day to day life.

A. METHODOLOGY

For our measurements, we have used the *HF32D RF Analyzer* by *Gigahertz Solution* which is a very easy to use RF radiation meter. This detector covers frequencies from 800MHz to 2.7GHz and therefore can be used to measure 4G/LTE, UMTS/3G, GSM, GPS, Radar, WLAN (Wi-Fi), and Bluetooth radiation densities. The device works on the principle of **Geiger counter effect** by deploying three log periodic antennas in three orthogonal directions.

In order to avoid disturbances from low-frequency EMR sources, the *HF32D RF Analyzer* suppresses sub 800MHz frequencies. The range and signal values of these devices are tuned to assess the EMR in accordance with the *Building Biology Standards* discussed in section III-B. If the power density exceeds the designated range, an attenuator *DG20* is used which increases the range by a factor of 100.

To execute the process of measurement taking, the EMR source devices were placed along the length of a measuring tape. The RF Analyzer was held from its rear end to avoid any reflections of EMR from the hand of the device holder. To accurately evaluate the radiation of the test device,the following procedure was followed:

- **Step 1**: The area around the test device was probed with RF Analyzer approximately 50 cm from the test device to obtain the direction with the highest level of radiation.
- **Step 2**: Next, the direction of the RF Analyzer was fixed at the point where the highest radiation level was recorded, and then the analyzer was rotated along it's longitudinal axis to maximize the reading of the instrument. This ensured that the antenna of the RF Analyzer was aligned with the plane of polarization of the EMR source.
- **Step 3**: Now, the relative orientation of the RF Analyzer and the test device was fixed and then the two devices were moved such that the RF Analyzer was placed on the measuring tape with it's direction of antenna parallel to the measuring tape, and it's base lying flat on the plane of the measuring tape.
- **Step 4**: For the remaining part, the test device was fixed at the beginning of the measuring tape in the orientation as obtained after step 3. If they were two devices being used in a particular scenario, the same steps were performed to fix the second device at the other end of the measuring tape.
- **Step 5**: Finally, the relative distance between the RF Analyzer and the test device was varied by shifting the RF Analyzer in fixed steps along the measuring tape to record the power flux density values. Let's call this relative orientation as 'x' and the corresponding values of power flux density obtained as P_x. Then by changing the orientation of the antenna to its orthogonal directions 'y' and 'z' we obtained two more sets of values, P_y and P_z respectively at the same positions where P_x was recorded.

Finally, the total magnitude of the power density at each position was calculated using equation 1 where P_x, P_y and P_z represent the power density levels received by the antennas oriented in the 'x', 'y' and 'z' orientation respectively.

$$\mathrm{P}_r = \sqrt{P_x^2 + P_y^2 + P_z^2} \tag{1}$$

An attenuator (*DG20*) was used with the RF Analyzer whenever the measured power density was beyond $2000\mu W/m^2$. The attenuator increases the range of the analyzer by a factor of 100.

For our investigation, we devised few scenarios based on frequently encountered situations in the day to day life of a normal user. The testing was done in an open field free from any sources of electromagnetic radiation as shown in Fig 4.

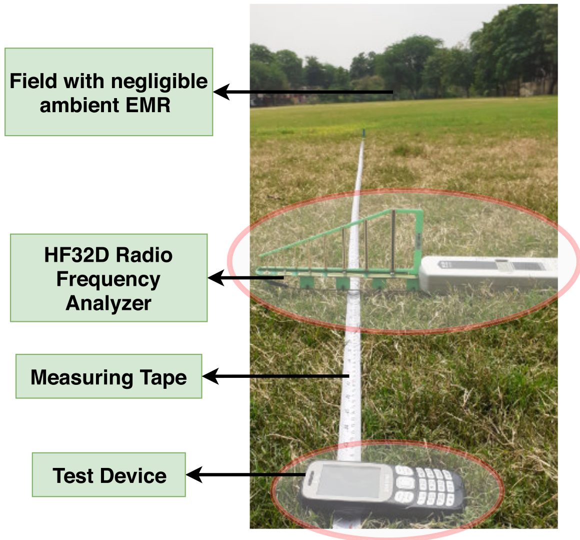
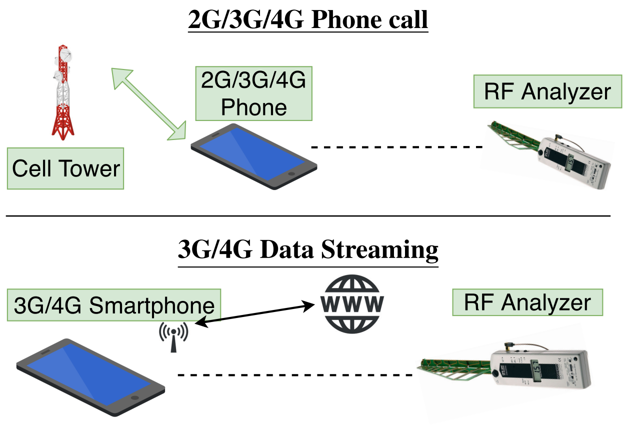
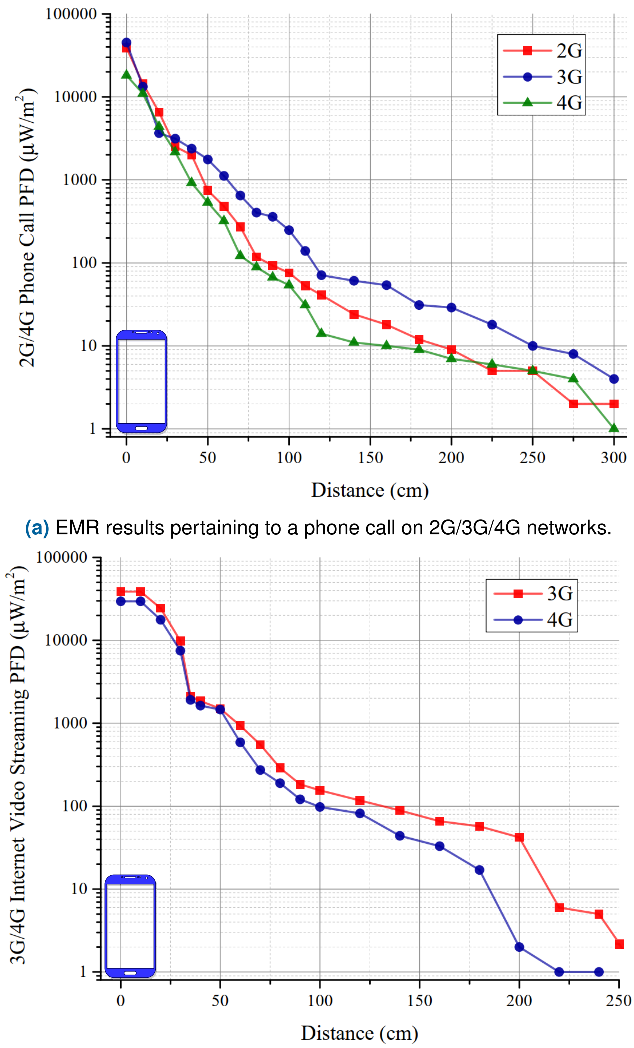


FIGURE 4. The location for testing was an open field with ambient Power Flux Density less than 5 $\mu W/m^2$.

TABLE 3. Experimental setup for cellular devices.





(a) EMR results pertaining to a phone call on 2G/3G/4G networks.

(b) EMR results pertaining to data streaming on 3G/4G networks.

FIGURE 5. EMR results pertaining to cellular devices.

B. EMR DUE TO CELLULAR DEVICES

Table 3 shows schematics of the experimental setups used for analysing cellular devices. Two cases were considered: Phone calls on 2G/3G/4G networks and data streaming on 3G/4G networks.

1) 2G/3G/4G PHONE CALL

The power flux density getting emitted from the mobile device which is put on call is recorded according to the above procedure. All other communication channels from the device such as Bluetooth, infrared, Wi-Fi and GPS were turned off. The results are plotted in Fig. 5(a).

In Fig. 5(a), we can see that the same smartphone emits most radiation on the 3G network, second highest on 2G network and least on the 4G network at almost all distances. While performing a phone call, at a very close range, the PFD measured is 43112, 38907 and 18172 $\mu W/m^2$ on 3G, 2G and 4G networks respectively. The close range radiation in all three cases is above 1,000 $\mu W/m^2$ which is classified as 'extreme concern' according to the Building Biology Standards and 'very far above normal' according to the AMA standards. The radiation is around 10,000 times higher than the precautionary action level recommended by the BioInitiative Guidelines (3 - 6 $\mu W/m^2$). But these values are certainly within the ICNIRP reference values for general public exposure which are between 9,500,000 $\mu W/m^2$ for 2G networks and 10,000,000 $\mu W/m^2$ for 3G and 4G networks. This implies that phone calls performed on 2G, 3G and 4G devices are safe in terms of thermal effects, i.e., a user will not face any health issues arising from tissue heating, but he/she is certainly at risk of developing health issues from non-thermal, chronic exposure and biological effects.

Near the test location, it was found that the nearest 2G, 3G and 4G BSs were all located on the same cell tower. Therefore, the observation of PFD levels (3G > 4G > 2G) network cannot be attributed to farther 3G/4G BSs. To be able to explain the exact reason for higher EMR emission of the smartphone on 3G networks compared to 4G and 2G networks requires thorough analysis of 2G, 3G and 4G antennas used on the smartphone, including their three-dimensional radiation patterns, and antenna configurations which are beyond the scope of this work.

At about 50cm away from the phone, the radiation level drops below 1,000 $\mu W/m^2$ which comes in the next category of 'severe concern' and 'far above normal'. Therefore the use of wired handsfree earphones/headphones is recommended which generally have a standard length of 1.2m, and by keeping the phone at about 1 m from the user, a good level of safety can be achieved.

2) 3G/4G DATA STREAMING

The mobile device used for this setup was Samsung Galaxy M30. To ensure continuous data transmission from the cell tower to the smartphone, a long HD video was streamed on the phone. The measured power flux density values are plotted in Fig. 5(b).

From Fig. 5(b), it is evident that the PFD of a 4G network is lesser than 3G networks at all distances during data transfers. At very close distances the radiation reaches 38798 and 29682 $\mu W/m^2$ for 3G and 4G networks respectively which is a situation of 'extreme concern' or 'very far above normal' according to Building Biology standards. At a distance of approximately 50 cm, the radiation in both cases drops down to about 1,000 $\mu W/m^2$ which is categorized as a situation of 'severe concern' or 'far above normal'. Smartphones are extensively used to stream videos and therefore it is recommended to keep the phone at least 50 cm away on a table to ensure that the user is exposed to a PFD less than 1,000 $\mu W/m^2$. Therefore, 4G networks must be preferred to 3G networks for data consumption. The scenario of 3G/4G Data streaming is similar to the situation of 2G/3G/4G since all the measured PFDs are well within the range of ICNIRP reference values for general public exposure, but pose serious health risks when seen in accordance with the Building Biology, AMA and BioInitiative standards.

3) 5G AND BEYOND

The testing of all the devices in this work has been carried out in India, where 5G networks are projected to be deployed by the year 2021. Therefore, measuring PFD levels for devices communicating on 5G networks could not be included in this work. 5G is set to use frequencies between 30 GHz and 100 GHz and would have a bandwidth of 60 GHz, which is much higher than all previous generations. Owing to the increased frequency, the wavelengths in 5G communications will be in the order of few millimeters. Shorter wavelengths travel shorter distances; therefore, 5G networks will be much denser compared to existing networks. This necessitates that more base stations be placed at much closer distances in order to achieve good coverage. In 3G cellular networks, the density of BSs is about 4-5 BSs/km^2, and the area served by each BS is large and therefore called a *macrocell*. In the case of 4G (LTE) networks, the BS density is about 8-10 BSs/km^2, the coverage of each BS is lesser and referred to as a *microcell*. However, in the case of 5G networks, the BS density is expected to be increased to about 40-50 BSs/km^2 due to the high propagation loss of millimeter wave technology. The area served by each BS in 5G networks is very small and is commonly called a *small cell*. The shorter millimeter waves would also not be able to penetrate building walls effectively. Therefore, the 5G architecture will separate indoor and outdoor networks, which means there will be separate access nodes for indoor users. 5G BSs will also be installed on street light poles meaning that people will be extremely close to the BS antennas, whether they are indoors or outdoors. In addition, 5G will also employ relay nodes that amplify the wireless signals from the BSs before they reach the device. The high data rate requirement of 5G, which is around 1000 times more than 4G, is expected to be solved by the use of massive-MIMO, which incorporates a large number of antennas. Thus, 5G networks contain *Macrocells*, *microcells*, *relays*, street light access points and separate indoor nodes, which operate simultaneously all the time.

Due to the extremely high density of BSs, street light access points, separate indoor BSs, relays and Massive MIMO technology employed in 5G, a person will be exposed to very high levels of PFDs, whether he is indoors or outdoors, or whether or not he is using any wireless devices in close proximity. In other words, it may be suspected that even the ambient PFD which a person is exposed to in most situations throughout the day may fall under the category of 'Severe Concern' according to the Building Biology Standard, 'Far above normal' according to the AMA standards, and may be higher than the precautionary action level recommended by the BioInitiative Guidelines. If 5G networks are deployed without careful analysis of expected exposure levels, almost all people in the area of coverage may be exposed to dangerous levels of PFD, the outcomes of which, in the near future, may turn out to be calamitous.

Currently, South Korea, United Kingdom, Germany, and the United States are at the forefront of 5G network deployment, with several companies already providing 5G services in these countries [12]. It is strongly suggested that a study similar to the one in this paper be conducted in these countries, by correlating the findings with the standards mentioned in section III in order to get a consistent view of radiation exposure in 5G networks as compared to previous generations. This would provide much-needed insight and caution to all countries that are yet to adopt 5G.

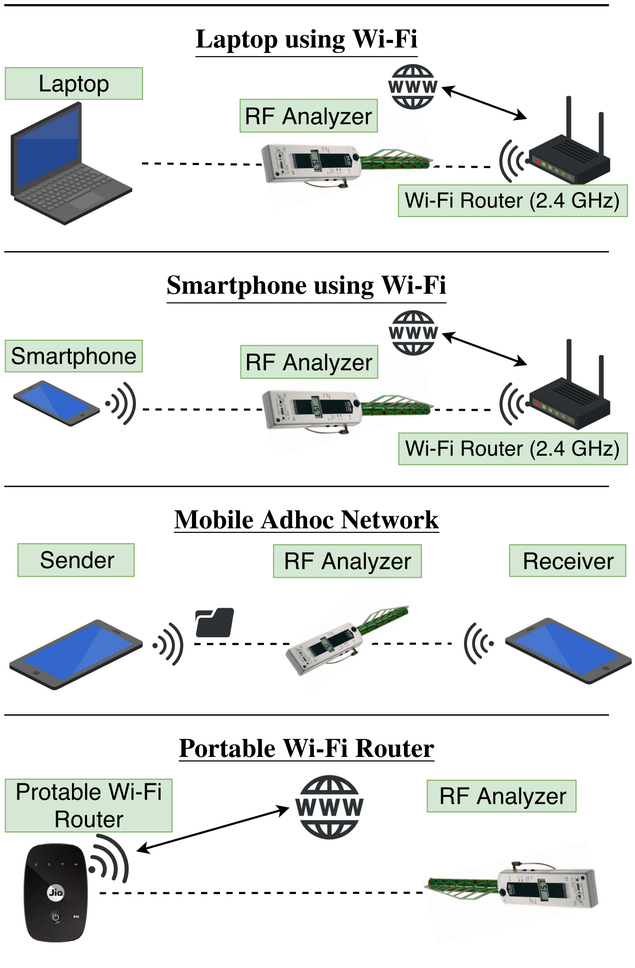
C. EMR DUE TO Wi-Fi DEVICES

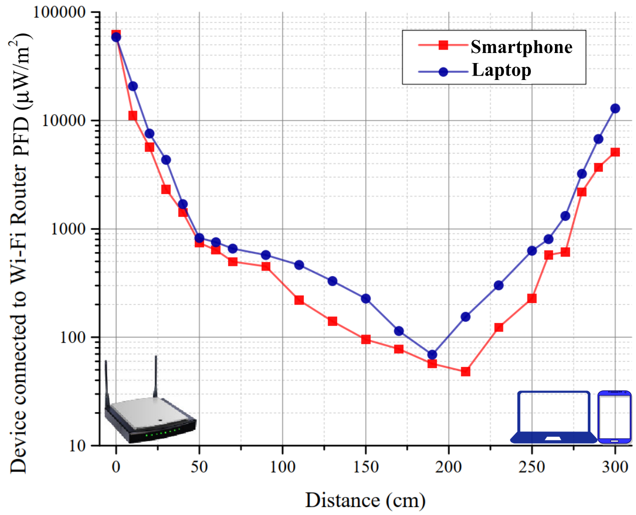
Table 4 shows schematics of the experimental setups used for analysing Wi-Fi use cases. Three cases were considered: Laptops/Smartphones connected to Wi-FI routers, Wi-Fi Mobile adhoc networks, and portable Wi-Fi hotspots/routers.

1) LAPTOP AND SMARTPHONE CONNECTED TO Wi-Fi ROUTER

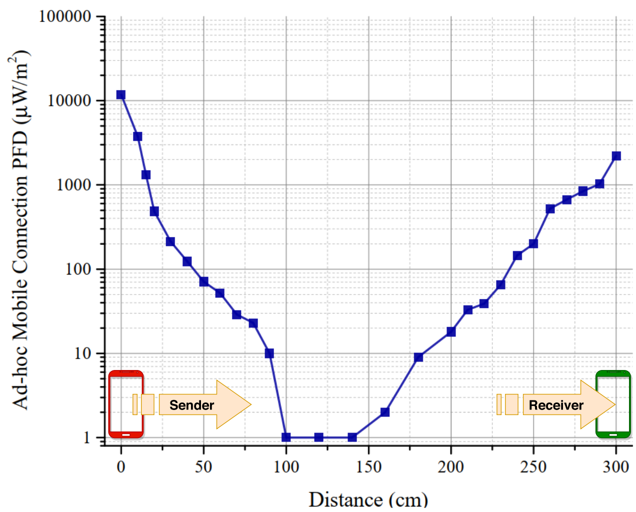
The laptop used for this setup was Lenovo Z51-70 which was put on airplane mode with only Wi-Fi turned on. The laptop was connected to the Wi-Fi Router operating at 2.4 GHz. The devices were kept facing each other as shown in Table 4. The power flux density readings are plotted in Fig. 6(a).

TABLE 4. Experimental setup for Wi-Fi devices.

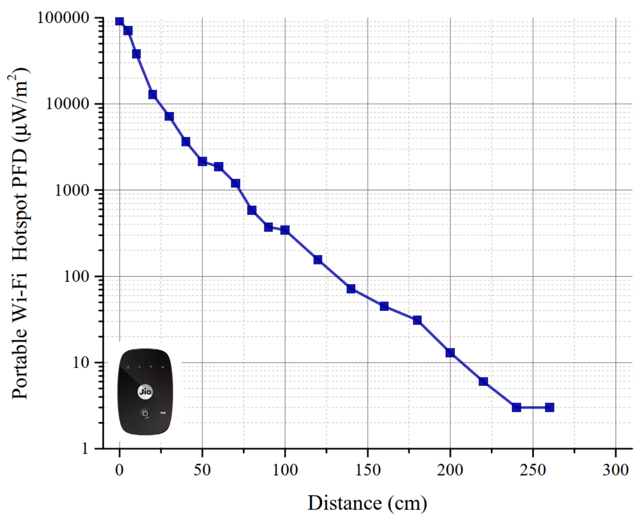




(a) EMR results pertaining to a smartphone/laptop connected to a Wi-Fi router.



(b) EMR results pertaining to smartphone ad-hoc network.



(c) EMR results pertaining to portable Wi-Fi router.

FIGURE 6. EMR results pertaining to Wi-Fi devices.

Comparing the scenario of a laptop and a smartphone connected to a Wi-Fi router, it can be inferred from Fig. 6(a), that the effect of the router on the PFD dominates until a distance of about 1.7m from the router. Just next to the router the PFD is about 60,000 $\mu W/m^2$ and drops below 100 at 1.7m from it. So, it advisable to always stay 1.7m away from any Wi-Fi router, whether you are using a laptop or a smartphone. Up to a distance of about 100 cm, the effect of the smartphone or laptop on the PFD dominates. The PFD measured at close proximity of the smartphone is 5123 $\mu W/m^2$ and 12886 $\mu W/m^2$ in the case of a laptop, which is more than 2 times greater than the latter. The reason for this is attributed to PCIe antennas used in the laptop which are designed for better connectivity in terms of range and data speeds. Therefore, smartphones should always be preferred in use cases where a laptop is not absolutely necessary. The PFD in both cases drops below 1000 $\mu W/m^2$ at a distance of approximately 50 cm. Although this PFD still falls in the category of 'severe concern' or 'far above normal' according to the AMA standards and is not to be considered safe, it is still better than the category of 'Extreme concern' or 'very far above normal'. Thus, it is better to keep laptops on a table and operate them from an arm's distance or keep the smartphone on a table while watching lengthy videos. Keeping a laptop on the lap or keeping a smartphone connected to the router in the pocket for long durations would result in dangerous amounts of radiation directly entering the body.

2) MOBILE AD-HOC NETWORK

Two smartphones (Samsung Galaxy M30 and Redmi Note 5) were connected using Wi-Fi Direct technology to form a mobile Ad-hoc Network and a large file was transferred between them. The power flux density readings along their line of sight are plotted in Fig. 6(b).

A hotspot is created between two devices and is meant to handle several connections at a time, which explains why the PFD on the side of a sender (11819 $\mu W/m^2$) is 5 times higher than that of the receiver (2223 $\mu W/m^2$) at a very close range as shown in Fig. 6(b). At a distance of about 1 m from both the devices, the PFD drops below 10 $\mu W/m^2$ which is a situation of 'slight concern' or 'slightly above normal'.

3) PORTABLE Wi-Fi ROUTER

Nowadays, portable Wi-Fi routers/hotspots which work on the 4G network are very popular due to their portability, ease of use with almost no setup time. In our measurement, we used the portable Wi-Fi hotspot to measure the power flux density emitted from the device upto 3 m in the direction of maximum radiation. The readings are plotted in Fig. 6(c). Although these devices are very easy to use and portable, they emit a high amount of radiation 92237 $\mu W/m^2$ at very close distances. This is because portable Wi-Fi routers are connected to the 4G network and simultaneously function as Wi-Fi routers capable of handling multiple connections at a time. This is the highest reading we recorded among the devices considered in this paper and falls in the category of 'extreme concern' or 'very far above normal'. The PFD drops below 1000 $\mu W/m^2$ at about 75 cm and below 10 $\mu W/m^2$ at 200 cm. By keeping the device about 200 cm or 2 m away from the user, one can attain a situation of 'slight concern' or 'slightly above normal'. From all the cases mentioned above, the lowest radiation observed while accessing the internet is in the case of a smartphone connected to a Wi-Fi router followed by a laptop connected to the Wi-Fi router. It should also be noted that accessing the internet via Wi-Fi routers involves less radiation in general than accessing the internet via cellular networks.

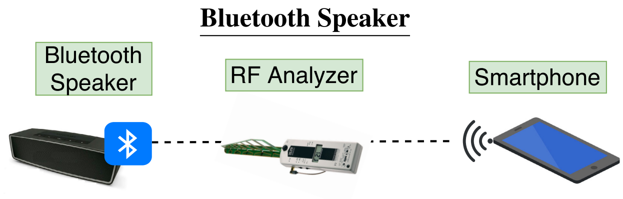
In terms of health risks, it can be concluded that Wi-Fi technologies also pose serious health risks in terms of chronic exposure, non-thermal, and biological effects of EMR but will not lead to any tissue heating or health risks arising from tissue heating.

D. EMR DUE TO BLUETOOTH DEVICES

1) BLUETOOTH SPEAKERS WITH AUDIO STREAM

Table 5 shows the schematic of the experimental setup used for analysing a Bluetooth speaker. A Bluetooth speaker was connected to a smartphone via Bluetooth wireless technology kept 3m away from the speaker. The power flux density between the two devices was measured and the results are plotted in Fig. 7.

TABLE 5. Experimental setup for bluetooth speaker.



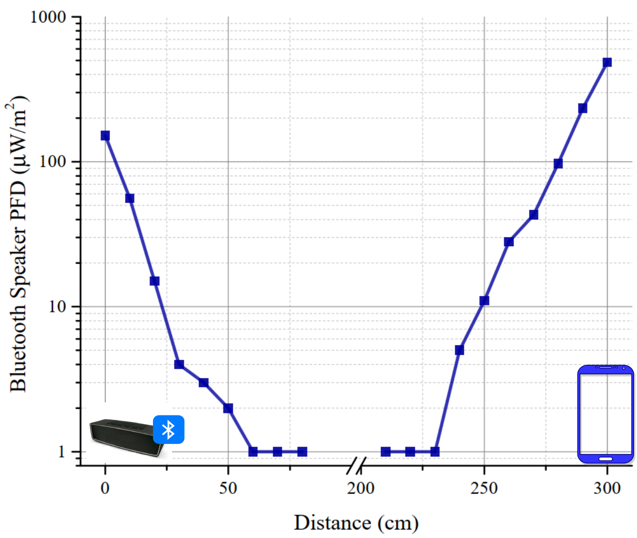


FIGURE 7. EMR results pertaining to Bluetooth speaker.

In Fig. 7, it can be seen that the highest reading just next to the Bluetooth speaker is 487 $\mu W/m^2$ and just 152 $\mu W/m^2$ near the smartphone. The PFD drops below 10 $\mu W/m^2$ at about 50 cm from the smartphone and 25 cm from the speaker which is a scenario of 'slight concern' or 'slightly above normal'. Therefore it is recommended to keep the smartphone at least 50 cm away, and the speaker at least 25 cm away from the user while playing the music.

2) BLUETOOTH EARPHONE

Wireless earphones are very quickly replacing wired earphones due to ease of use. A subject was chosen to wear Bluetooth earphones connected wirelessly to a smartphone (Samsung galaxy M30) kept in his trouser's right pocket. A long audio file was played to ensure continuous communication between the devices. We measured power flux density in different areas around the body as shown in Fig. 8.

3) SMARTWATCH CONNECTED WITH PHONE

Many people these days are using smartwatches to track their health and routine. Therefore it becomes very important to study whether the radiation coming from the usage of smartwatch is adversely affecting users health or not. The subject was made to wear a smartwatch on his right hand which was connected to smartphone (Samsung Galaxy M30) via Bluetooth, and the smartphone was kept in the subject's right trouser pocket. The power flux density was measured in different areas around the body as shown in Fig. 9.

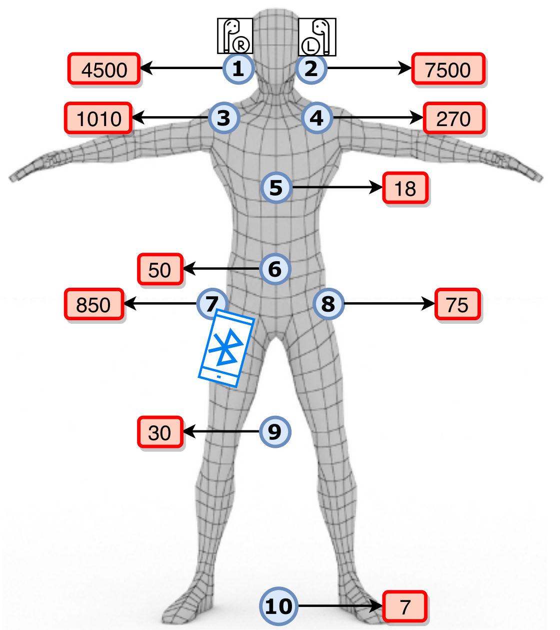


FIGURE 8. EMR readings on different parts of the body while wearing bluetooth earphones (in $\mu W/m^2$).

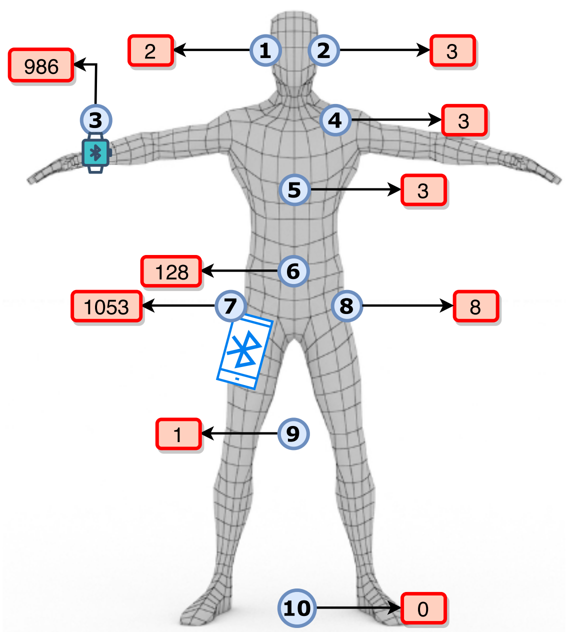


FIGURE 9. EMR readings on different parts of the body while wearing a smartwatch (in $\mu W/m^2$).

Based on the values of PFD shown in Fig. 8, it can be observed that the use of Bluetooth earphones heavily impacts the head region with PFDs in the range of 4000 - 8000 $\mu W/m^2$ which comes under the category of 'extreme concern' or 'very far above normal'. In the region of the pocket where smartphone is kept, the PFD is 850 $\mu W/m^2$ which is a situation of 'severe concern' or 'far above normal'. In the remaining regions, the PFD is not as significant. Thus, it can be said using Bluetooth earphones puts a person at risk of developing health issues related to non-thermal, chronic exposure and biological effects in the head, shoulder and pocket regions but is safe from any thermal effects of EMR exposure. In the case of a Bluetooth smartwatch, the radiation in the pocket region as well as near the smartwatch is about 1000 $\mu W/m^2$ (see Fig. 9) which can be considered a case of 'Extreme concern' and or 'Very far above normal'. Therefore, it is expected that a person may develop health issues arising from non-thermal, chronic exposure and biological effects only in the pocket and wrist regions. The observed radiation levels indicate that a user is not in any risk of health issues arising from thermal effects.

E. COLLECTIVE EXPOSURE

In most practical situations, there are several wireless devices functioning simultaneously in the vicinity of a person, which makes it becomes important to understand the collective radiation exposure due to all these devices. Here, we consider the case where a person is being exposed to EMR from Wi-Fi, Cellular and Bluetooth devices, namely, a laptop, smartphone, Wi-Fi router, smartwatch, Bluetooth earphones, and a Bluetooth speaker. We have considered these devices to ensure the best balance between worst-case exposure and the most probable set of devices that a person may use. In all practical situations, ambient EMR is always present. Therefore, our readings were taken in a practical test location where there was an ambient EMR of 5 $\mu W/m^2$.

For our measurements, we consider a test subject using his laptop kept on a desk, wearing a Bluetooth smartwatch on his left hand, and neck-band type Bluetooth earphones around his neck and also holding a smartphone to his right ear. The laptop is connected to a Wi-Fi router kept 50 cm away on the same table. The Bluetooth earphones are connected to the smartphone and playing music. The smartphone is put on call over the 4G network. A Bluetooth speaker is also kept on the same desk, which is connected to the laptop. Fig. 10 shows the test subject and the placement of various devices near him, and Fig. 11 the measured PFDs at several points near the test subject. At each test point, the orientation of the RF analyzer was adjusted to ensure the maximum reading.

As can be seen in Fig. 11, the measured PFD exceeded 10,000 $\mu W/m^2$ in all points except the leg region where a PFD of 500 $\mu W/m^2$ was recorded. This implies that the EMR in the leg region comes under the category of 'severe Concern' or 'far above normal,' while all other points showed a PFD of more than 10,000 $\mu W/m^2$ and thus come under the category of 'extreme concern' or 'very far above normal.' A PFD of 133,400 $\mu W/m^2$ near the Wi-Fi router, was the highest reading recorded in our test scenario, indicating that of all the devices, the Wi-Fi router was the most contributing factor to the cumulative exposure. Therefore, it is highly recommended to avoid keeping a Wi-Fi router on the table. Due to the proximity of the mobile phone, the region near the right ear is exposed to PFD of 36, 700$\mu W/m^2$. A PFD of 33, 600$\mu W/m^2$ recorded near the left arm can be attributed to the Wi-Fi router, smartwatch and laptop together. The PFD recorded near the chest, torso and groin region: 12300, 5700

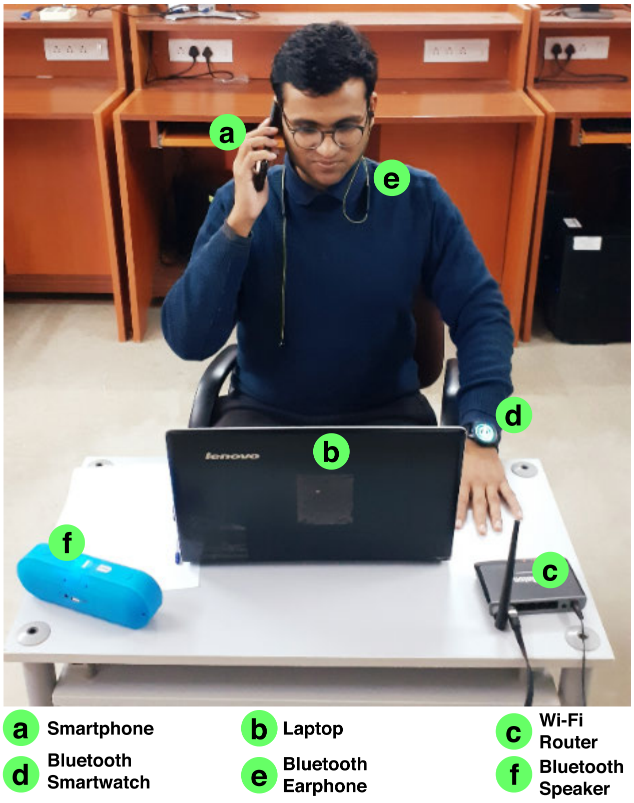


FIGURE 10. Placement of different devices in a collective exposure scenario (in $\mu W/m^2$).

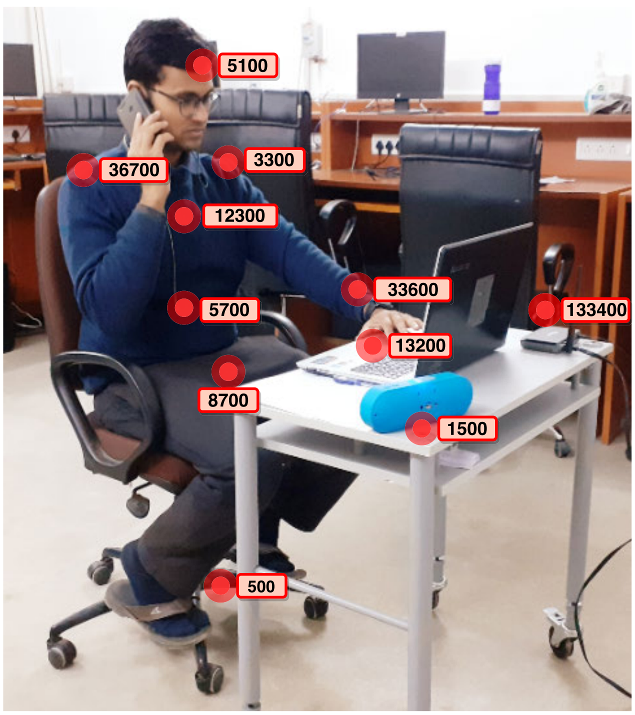


FIGURE 11. EMR readings at different points of in a collective exposure scenario (in $\mu W/m^2$).

and $8700\mu W/m^2$ respectively are all in the category of ‘extreme concern’ or ‘very far above normal.’ The exposure in the groin region in a cumulative exposure scenario is several times higher than the case considered in section IV-D.2, and IV-D.3, where a smartphone was kept in the pocket while being connected via Bluetooth to wireless earphones and smartphones respectively. A PFD of $13, 200\mu W/m^2$ was recorded near the keyboard of the laptop. This high reading is attributed to the laptop’s Wi-Fi antennas, which are located on top of the screen. Thus, a wired connection to the router should always be preferred to Wi-Fi. Based on the above discussion, it can be concluded that keeping many wireless devices in close proximity is extremely dangerous in terms of non-thermal, chronic exposure and biological health effects but will not lead to any thermal effects since all measurements are within the ICNIRP reference values for general public exposure.

V. HEALTH RISKS AND HAZARDS OF EMR EXPOSURE

From released reports and published articles it is evident that there is a strong correlation between distance from cell towers and variety of EMR related health complaints. People who lived in the vicinity of cell towers or base stations reported health issues such as insomnia, fatigue, headaches and nausea. Some of these people were even diagnosed with serious health diseases such as leukemia, Alzheimer’s, Autism, ASD, neuro-psychiatric issues, brain tumors and breast cancer. BioInitiative report has compiled more than 1800 scientific research articles which report serious impact on human and animal bodies like abnormal gene transcriptions, genotoxicity, DNA damage, chromatin condensation, loss of DNA repair capacity, reduction in free-radical scavengers, neurotoxicity, decreased sperm morphology and impaired development of brain and cranial bone. In this section we have summarized the adverse health effects of EMR exposure.

A. CANCER

The International Agency for Research on Cancer (IARC), an independently financed organisation classified Radio-frequency RF EMR under Group 2B carcinogen which means that there is a possibility that RF may be carcinogenic to humans [13]. However, Hardell and Carlberg [14] claim that there is clear evidence of cancer from long term, low level exposure to pulsating and non-ionizing EMR. Their findings warrant IARC to put RF EMR in Group 1: known carcinogen. Another study by The National Toxicology Program (NTP) conducted studies to evaluate potential health hazards and the risk of cancer from RF Radiation. Mice and rats were used as test subjects and were tested on exposure to RF Radiation in the 2G and 3G spectrums (700 - 2700 MHz). This study reported clear evidence of tumor in the hearts, brains and adrenal glands of male rats [15].

Although, not many biophysical mechanisms have been proposed regarding how RF Radiation leads to tumor causing effects, the thermal exposure limits are set solely based on one observed phenomenon which is the amount of power absorbed per mass of tissue or in other words, how much the tissue is getting heated. The thermal limits are specified such that any RF radiation above these limits starts to heat the body and shows observable effects like disturbance of blood flow and metabolism. Nonetheless, few studies have reported that even at radiation levels below the accepted limit (and legally defined) for human exposure there are signs of tumor-promoting effects [14].

B. PREGNANCY AND INFERTILITY

A strong correlation between male infertility and EMR from mobile phones has been asserted by several researchers [16]. A case study [17] was conducted on male wistar albino rats who were exposed for 14 days, 15 minutes each day to high EMR. The radiation had impacted their testicular architecture and enzyme activity. It was shown that EMR from mobile phones induces an oxidative stress in testicular tissues and ultimately results in decrease of semen quality and lower sperm motility. The severity of oxidative stress depends on usage patterns of the mobile phone owner [17]. In a 2017 study to evaluate the effect of 4G-LTE EMR on sperm formation in male rats, it was concluded that longer durations of exposure results in decreased spermatogenesis [18]. Incidents have been reported where telecom workers who were accidentally exposed to high EMR doses developed skin burns and injury to heat-sensitive tissues such as the lens of the eyes, the testicles and the brain, leading respectively to cataract, male infertility and seizures [19]–[21].

The carcinogenic nature of EMR which results in mutation of sperm cells as well as testicular cancer has also been reported [22]. Thus, the probability that future generations will inherit unhealthy or low-immunity genes is also increased. In a case study which involved exposing pregnant rats to EMR during different stages of pregnancy, uterine congestions, dead and reabsorbed fetuses, hemorrhage, unequal and asymmetrical distribution of fetus implantation sites, malformation, hematoma, short tails and growth restrictions were observed [23].

According to [24], children whose mothers used cell phones during pregnancy had 25% more emotional problems, 35% more hyperactivity, 49% more conduct problems and 34% more peer problems.

C. AUDITORY SYSTEM DAMAGE

When a mobile device is actively connected with the cellular network, all the components of the auditory system including the skin, external, middle and inner ear, cochlear nerve and the temporal lobe surface absorb RF energy. Moreover, it is known that the outer hair cells in the cochlea are highly sensitive to a wide variety of exogenous and endogenous agents which include externally applied electric and magnetic fields [25]. EMR is damaging to unprotected or externally exposed biological tissue such as the outer hair cells in the cochlea. People who have an overactive cortical stress network in the brain are more vulnerable to tinnitus [26].

A common disease or effect is *Tinnitus*, which is in most cases a neurological disorder. A person suffering from tinnitus perceives high-frequency ringing among other sounds which are externally non-existent. Such people generally report poor quality of sleep, and several difficulties throughout their daily life. In the worst cases, even suicides have been reported. In light of EMR, it is relevant to note that the number of tinnitus cases reported since the last few decades has increased several folds [27]. Studies have shown the evidence that the main cause for such an increase can be attributed to the widespread and long-term usage of cellular phones, particularly in those cases where one ear is much dominantly used over the other [28].

Another phenomenon to be aware of is *RF Hearing* which was confirmed to exist as early as 1960s. Although RF energy is electromagnetic in nature, some of it is converted into acoustic energy both within and outside the cochlea and is perceived as a sound centered at about 5 KHz. The exact frequency may vary depending on the dimensions of the subject's head [29].

Dabholkar *et al.* [30] reviewed several long term case studies and concluded that long term intensive use of mobile phones does lead to hearing losses. Prolonged use (> 1 year) of mobile and cellular technology may decrease the ability of a person to hear high-frequency sounds. The person is also more likely to develop acoustic neuroma, in which non-cancerous tissue develops on a nerve which links the inner ear with the brain. In advanced stages of acoustic neuroma, pressure is exerted on the brain which may result in dangerous neurological effects including vertigo, confusion, unsteadiness, facial numbness and headaches. But casual or infrequent usage does not lead to any immediately recognizable adverse effects or any significant damage to the auditory system.

D. EFFECTS ON CHILDHOOD DEVELOPMENT

Statistics show that in recent years, more children have begun using cellphones or smartphones compared to the elder generation. In addition, it is observed that the average age at which children nowadays begin using smartphones is also significantly lesser than before. Therefore it is expected that this population will absorb significantly more EMR radiation throughout their lifetime. The existing public safety limits for EMR exposure are not acceptably protective of public health, especially the young population including babies, neonate, fetus and embryo. EMR exposure to pregnant women have detrimental consequences on the future health of the child. The time a foteus spends in the mother's womb is a critical time of devleopment because the health problems that are once laid down in the cells or in epigenetic changes in the genome have life-long consequences on the health of that individual [31]

The young population are more vulnerable to EMR exposure because of their smaller body mass and rapid physical development, both of which magnify the impact of EMR on body. The differences in bone density and the amount of fluid in a child's brain compared to an adult's brain allow children to absorb greater quantities of RF energy deeper into their brains than adults [32]. It is known in the field of medicine that the brain tissue in children shows more electrical conductivity when compared with adults. This allows for more EMR penetration in proportion to the dimensions of the head. Effects on the nervous system which is still in developmental stages are also causes of concern. While anatomical development of the nervous system in children is finished, EMR could still hamper the functional development which generally progresses into adulthood [33].

E. BLOOD RELATED DISORDERS

Exposure to even very low intensity EMR can affect the blood-brain barrier by increasing it's permeability. Blood-brain barrier prevents the flow of toxins into sensitive brain tissues and when it's permeability increases due to exposure from EMR it no longer provides the protective barrier. Salford *et al.* [34] conducted a study and found that just single two hour exposure to EMR from cell phone results in an increased leakage of blood-brain barrier, and 50 days of such exposure can lead to neuronal damage. The EMR level as low as 0.001 W/kg can affect the blood-brain barrier and this limit is about 1000 times lower than the FCC (1.6 W/kg) and ICNIRP (2 W/kg) limits allowed. Research is required to investigate the damage done by EMR exposure on other barriers like the blood-placenta barrier (that protects the developing fetus), the blood-testes barrier (that protects developing sperm), the blood-ocular barrier (that protects the eyes) and the blood-gut barrier (that protects proper digestion and nutrition).

F. DNA DAMAGE

DNA molecules in our body directly interact with EMR. The double helical structure of DNA causes it to act like a *fractal antenna* [35]. The characteristic of a *fractal antenna* is that it interacts with wide range of frequencies. Therefore, the structure of DNA makes it vulnerable to damage from EMR exposure over the entire range of non-ionizing frequencies i.e. from extremely low frequency range (300 Hz to 3 kHz) to radio frequency range (3 kHz to 300 GHz). This interaction of DNA and EMR generates free radicals, produces stress proteins and causes gene mutations. Human DNA and stems cells are permanently damaged by EMR exposure as they do not have the ability to adapt to chronic exposures of EMR and thus DNA repair is not possible [36].

G. EFFECTS ON MENTAL AND COGNITIVE HEALTH

Many neurodegenerative diseases like Parkinson's disease, Alzheimer's disease and motor neuron disease are found to be caused and triggered by EMR exposure [37]. EMR damages the neurons of the brain, reduces the neuronal reactivity, prolongs their refractory period and increases the neural membrane conductivity. All such diseases mentioned above involve death of specific neurons and therefore are called neurodegenerative diseases.

As mentioned in the introduction of this section, people living in vicinity of cell towers and base stations are prone to develop many neuropsychiatric problems like tremors, numbness, headache, nausea, memory loss, dizziness, altered reflexes, depression and many other severe brain and cognition related health problems such as paralysis, stroke and psychosis [38], [39].

VI. PROTECTIVE MEASURES AND AMBIENT EMR MINIMIZATION

Based on the discussion in section V, it becomes very clear that the people exposed to EMR must adopt some preventive measures to limit their exposure to harmful RF EMR. In many situations such as those discussed in Section IV, we are exposed to EMR almost daily for prolonged periods of time. While it may not be possible to entirely eliminate such exposure, such as in workplaces, some protective measures could be taken by people to reduce the amount of EMR they absorb and thereby reduce the damage done to their bodies. In this section we present some techniques which are either based on externally attenuating the EMR before it hits the body and some techniques based on monitoring and deploying the EMR sources effectively and efficiently so as to minimize the ambient EMR levels. The techniques based on external attenuation have to practised on an individual level, while the ambient EMR minimization techniques can be practised on government and society levels only.

A. PROTECTIVE MEASURES

1) EMR ABSORBING CLOTHES

As a result of the research in the past decade suggesting the dangers of EMR on the human body, a variety of EMR absorbing clothing solutions began surfacing the market. Such clothing options incorporate surface-metallized fiber woven fabric in their apparels. Metals like copper, silver or aluminium are chemically deposited on ordinary knitting fabrics to obtain surface-metallized fiber knitted fabric. Such metals are known to attenuate EMR by scattering incident radiation [40]. While many manufacturers do claim a specific EMR absorbing efficacy in decibels over a certain frequency range, it cannot be said for sure whether the attenuation rating claimed by such clothes was obtained through well-designed tests. Such clothes are generally bi-layered, where the first layer reflects some of the incident EMR and the second (inner) layer absorbs the radiation which passed through the first layer [41]. The higher the decibel value, greater is the shielding capability. Most of the materials have a characteristic range of frequencies which they absorb. For example, a product that has an effect of 30 dB at 1 to 5 GHz would mean that the product blocks 99.9% of radiation in the wavelength range of 1 to 5 GHz, which includes most of the RF EMR encountered commonly: cell phones, Wi-Fi routers and bluetooth devices.

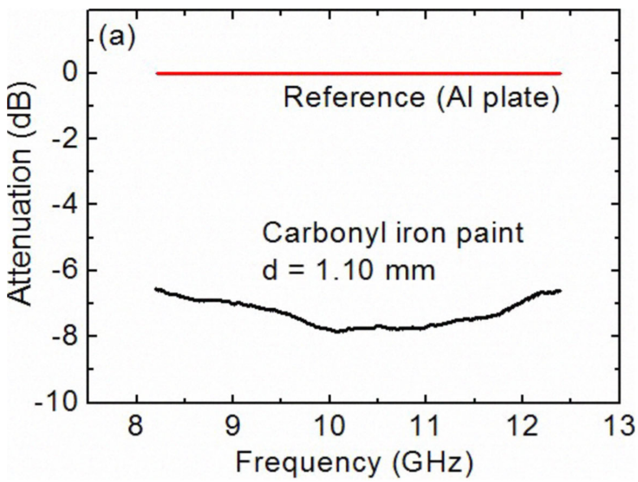
Metals are the best solution to reflect EMR. Hence, such clothing generally has metallic strands or metal silk fibers embedded within them which reflect incident EMR away from the wearer's body. Metal silk fibers are also blended with regular fabrics to obtain specially designed electromagnetic shielding fabrics which are used to make different clothing products such as curtains and blankets. Chemical deposition processes are also used to form a conductive metal plating on top of regular fabric. In any of the above mentioned varieties of EMR protective clothing, the shielding capability increases with the amount of metal used in the product.

Pregnant women, young infants and children, are especially recommended to wear radiation protective clothing due to their higher vulnerability to radiation absorption and damage. Workers who are exposed to abnormally high levels of EMR, such as cell tower repairmen need specially designed EMR reflective and protective clothing designed specifically for their occupation.

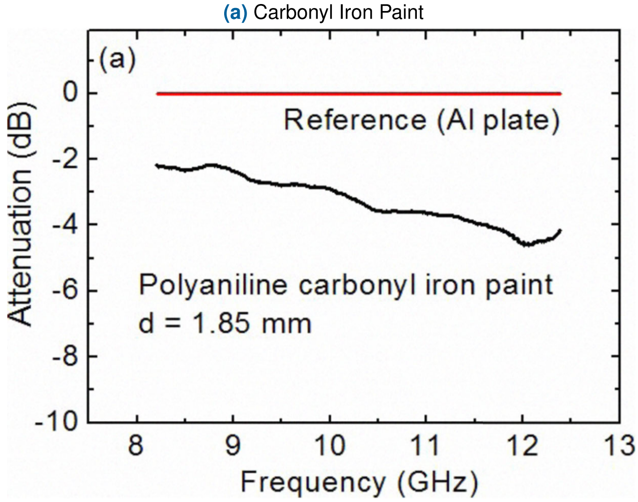
2) EMR ABSORBING/REFLECTING PAINTS

Many households are located very close to cell towers which have multiple antennas operating on them. The wall facing in the direction of the tower is most exposed to RF EMR. If it is unprotected, i.e, it does not have any absorptive/reflective coating, the people living in such homes are more prone to develop EMR related health issues as discussed in Section V. One very effective way to prevent high levels of EMR from penetrating the home is to use EMR absorbing/reflecting paints which are specially designed to absorb, reflect or scatter EMR in the RF frequency range as is emitted by the cell towers.It is desired to achieve high levels of attenuation across a wide frequency range.

Materials which have numerically equal values of permittivity and permeability and high loss tangents are more suited to be used in making EMR absorbing paints. The former characteristic guarantees good impedance mathching with the air and thus enable incident signals to enter the surface without any reflection. The latter characteristic enables the material to attenuate the EMR rapidly before it enters the home. By using such materials the reflection is also minimized. So, people standing outside the homes are also protected from high power EMR reflected from the walls of the homes. The power radiated from cell towers at certain frequencies may be much higher than others. EMR absorbing paints can address this problem as well because the frequency range at which maximum attenuation is achieved can be set by varying the thickness of the paint applied on the wall. Choosing a thickness to match complex permittivity and permeability can result in a considerable increase in the absorption bandwidth both at normal and oblique incidence of EMR. For example Folgueras *et al.* [42] have prepared two varieties of paints to absorb EMR. Both their formulation have a polyuerthane matrix. Carbonyl iron powder (10% w/w) and polyaniline (10% w/w) are the chemicals dispersed in the matrices of the two formulations respectively by mechanical agitation. The attenuation plots of these paints are shown in Fig. 12 (a) and (b) respectively. The paint of Fig 12 (a) achieves attenuation of 8 dB (84.1%) at 10 GHz and the paint of Fig 12 (b) achieves attenuation of 4 dB (60.1%) at 12 GHz. Such paints could be used to shield the EMR coming from 5G towers which are much higher than any RF communication used till date. To ensure the best protection, on-site testing can be done to accurately determine the frequency at which there is maximum radiation and also the minimum attenuation required to ensure that the residents are protected from any harmful effects. The customers can pass on these specifications to the manufacturer who can then adjust the chemical composition and also suggest the thickness required according to the customers' needs. This would ensure maximum protection at minimum expenditure.



(a) Carbonyl Iron Paint



(b) Polyaniline Carbonyl Iron Paint

FIGURE 12. Performance of EMR absorbing paints [42].

3) AEROGEL

Aerogels are a class of high performance EM radiation absorbing materials designed by fitting several nanosheets of graphene into three-dimensional structures [43]. Their excellent absorption characteristics is due to their high surface area and dielectric loss [44]. The reflection loss (RL) of a material is a characteristic of the input impedance Z_{in}, and output impedance Z_o. RL and Z_{in} are evaluated as follows:

$$\mathrm{RL(dB)} = 20\log\left|\frac{Z_{in}-Z_0}{Z_{in}+Z_0}\right| \quad (2)$$

$$Z_{in} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left(j\frac{2\pi fd}{c}\sqrt{\varepsilon_r\mu_r}\right) \quad (3)$$

TABLE 6. Comparison of different aerogels.

Name of Aerogel	EA Bandwidth	Highest Reflection Loss	Range for EMR absorption
Three Dimensional Polypyrrole [3D-PPy/Paraffin]	6.2 GHz	-25 dB @ 3 mm pellet at 10 GHz	7 GHz ∼13 GHz
Graphene Aerogel Composites [CF@G]	4.1 GHz	-30.53 dB @ 2.5 mm pellet at 14.6 GHz	12 GHz ∼16 GHz
Graphene Aerogel Composites with polypyrrole coating [CF@G@PPy]	4.1 GHz	-45.12 dB @ 2.5 mm pellet at 14.6 GHz	12 GHz ∼16 GHz
Spongelike Polypyrrole aerogel with Reduced Graphene Oxide [S-PPy/RGO]	6.76 GHz	-54.44 dB @ 3 mm pellet at 12.76 GHz	10.20 GHz ∼16.96 GHz

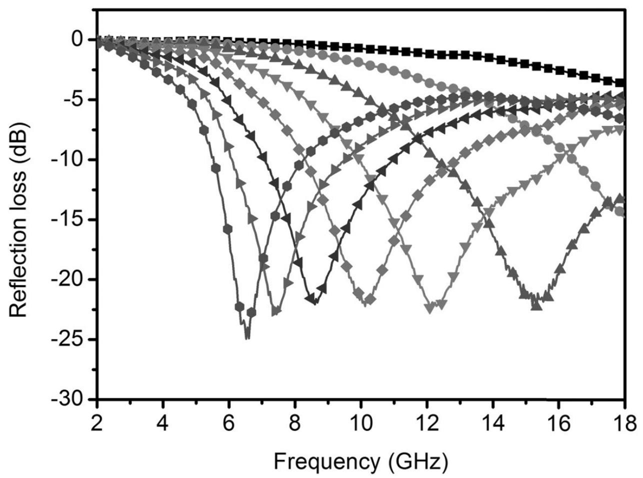


FIGURE 13. RL vs frequency of 3D-PPy aerogel (thickness varying from 1.5 to 5.0mm). [47].

In the above equations, Z_o is the impedance of the, ε_r is the complex permittivity, μ_r is the relative complex permittivity, f is the frequency, d is the material thickness, and c is the speed of light. According to fundamental mechanism of electromagnetic absorption, the most effective absorption would take place when the impedance matching conditions between the material and the free space is achieved [45]. Plots of reflection loss (RL) vs frequency such as in Fig. 13 are prepared for various thicknesses of the aerogel material. Such plots may be used to choose the best material for an application considering into account the most prominent frequency of radiation and the thickness of absorbing material permissible. The frequency at which highest RL occurs varies with the thickness of the aerogel as can be seen in Fig. 13. As the thickness of the aerogel pellet is varied, new phase matching conditions have to be established in order to maintain the RL [46].

Wang *et al.* [43] have prepared ultralight and mechanically strong 3D composite graphene aerogels with the use of waste cigarette filters. Their composite aerogel showed a minimum RL of −30.53 dB with a bandwidth of 4.1 Ghz. On coating with polypyrrole, a conducting material, the new composite showed minimum RL of −45.12 dB. Similarly, Xie *et al.* [47] prepared a self-assembled ultralight 3D polypyrrole (3D-PPy) aerogel, a composite which can reach an effective Electro-Magnetic bandwidth of 6.2 GHz with minimum RL of −25 dB. Wu *et al.* [48] prepared a spongelike self-assembled ultralight aerogel which showed a minimum RL of −54.44 dB with a bandwidth of 6.76 GHz. The above mentioned aerogels and their absorption characteristics are summarized in Table 6.

B. AMBIENT EMR MINIMIZATION

1) OPTIMAL MOBILE NETWORK DEPLOYMENT

With ever-growing consumer demands for telecommunication services and the deployment of 5G technology soon to come, many new base stations will have to be deployed over the already existing 2G/3G and 4G network. Therefore, it becomes very important to achieve optimal deployment of cellular Base stations or wireless access points in order to minimize radiation levels. Compared to most optimization solutions in research [49]–[52], which have considered deployment cost, coverage level and base station capacity in the objective function, Salcedo-Sanz *et al.* [53] have considered an additional criterion, electromagnetic pollution. They have proposed a solution called Grouping Coral Reefs Optimization (GCRO) and demonstrated its effectiveness when applied to a Mobile Network Deplyment Problem (MNDP). Deruyck *et al.* [54] have presented a tool which achieves different levels of optimization for power consumption and human exposure in LTE networks. Plets *et al.* [55] have developed a gentic optimization algorithm for Wireless Local Area Networks (WLANs) which optimizes the Exposure Index (EI) [56] taking into account all sources of exposure such as uplink, downlink and the uplink of other users, realistic duty cycles while simultaneously ensuring Quality of Service (QoS) to all users.

Chiaraviglio *et al.* [57] have proposed important guidelines to be followed during deployment of 5G base stations in order to achieve EMR-aware 5G networks. These guidelines include modelling of 5G radio technologies which helps to select the proper configuration of the installed equipment for each considered site, modelling of the generated EMR levels over the territory which allows for a fine-grained antenna site characterization based on the knowledge of the radiation pattern and the emitted power of each antenna in the site, integration of current and future EMF limits, modelling of the set of candidate sites based on idealized distributions and operator-based constraints, modelling of 5G traffic demands and QoS based on spatial and temporal fluctuations that can characterize the radiated power demand and modelling of 5G network topologies.

2) ELECTROMAGNETIC POLLUTION MONITORING USING WIRELESS SENSOR NETWORKS

With new base stations being installed on daily basis, monitoring EMR pollution on a real-time basis becomes essential to detect and locate potentially dangerous EMR levels and notify corresponding authorities to ensure safety of nearby people. In this regard, Nouh *et al.* [58] have proposed an EMR pollution monitoring system using a Wireless Sensor Network (WSN) based framework. Their system uses a genetic algorithm on EMR data acquired from WSN nodes do detect and report any EMR limit violations. The WSN nodes are deployed uniformly over an area and are equipped with sensors to detect EMR in the frequencies which are most prevalent.

VII. PROACTIVE PREVENTIVE TECHNIQUES

Certain simple steps can be taken by any individual to avoid EMR exposure. Spreading awareness about dangers and health hazards of EMR in schools, hospitals and other areas having sensitive population such as pregnant women, small children and old people, and giving them simple suggestions based on their surroundings, can help lot of citizens avoid EMR related health issues without spending resources on integrating and deploying EMR attenuating technology. We have listed few such *proactive and common sense* measures to minimize unnecessary and needless EMR exposures keeping in mind various environments and operating conditions:

1) In residential places such as homes, at study table and other places where people sit for long periods to use internet, we can have ethernet cable to avoid getting exposed to 2.4 GHz Wi-Fi signal. Many switches to control the power to Wi-Fi router can be installed throughout the house to readily switch off the Wi-Fi radiation when not in use. The windows can be covered with transparent EMR absorbing/reflecting thin film and outer walls can be painted with EMR absorbing paints. Use of landlines for long talks should be preferred over mobile phones and cordless phones. Rooms of children below the age of 12 should be particularly safeguarded from EMR as they are more prone to EMR related health issues.
2) In hospitals and medical institutions, it is especially important to implement guidelines regarding EMR safety as hospitals cater to very sensitive population such as pregnant women, newborn babies, and unhealthy people. Hospitals should not adopt full Wi-Fi coverage technology. Preferably they should give ethernet ports to all the doctors and hospital wards. Government should lay guidelines to not allow deployment of Base Station or Cell tower in near vicinity of hospitals. Units for sensitive population like ICU, CCU, NICU and operation theaters should avoid all sorts of devices which use wireless communication such as wireless incubators and remotely operated instruments. Only those sources of EMR should be used which are meant for medical purposes. Pregnant women should be educated to avoid prolonged use of mobile devices, laptops and other wireless devices.
3) In educational institutions, there is a trend to shift to modern technology like wireless projectors in smart classrooms, campus wide Wi-Fi access, use of digital notebooks, etc. As we have mentioned in section V, children are very sensitive to EMR and health issues like autism and impaired mental development are becoming very common among young population. Schools where children spend almost 8 to 10 hours need to minimize the ambient EMR levels inside the classroom by using EMR absorbing paints and window films. School authorities should give special rules and guidelines for high population density zones such as classrooms and school buses, which get really high EMR levels due to everyone using wireless devices simultaneously. If all classrooms cannot be made to comply with EMR safety standards, schools should construct special classrooms to maintain 'no wireless' condition, and allow students to opt for it who believe their academic, social or behavioural progress is being hindered by EMR related health issues.

VIII. DISCUSSIONS

Currently employed public exposure limits do not provide sufficient protection to people both in terms of long-term and short-term exposure. The exposure limits specified by ICNIRP take into account only the thermal effects and not the non-thermal biological effects in determining their limits. The ICNIRP safe exposure limits for general public for the wireless technologies discussed in this paper are between 4,000,000 $\mu W/m^2$ to 10,000,000 $\mu W/m^2$ which is several orders of magnitude higher than the limits prescribed by the Building Biology, AMA and the BioInitiavtive standards. While exposure levels within the limits prescribed by ICNIRP only guarantee safety from the thermal effects of EMR

TABLE 7. Recommendations for using cellular, Wi-Fi and Bluetooth devices.

Device Type	Recommendations
Cell Phones/ Smartphones on cellular networks	1. Network: For internet connectivity, prefer Wi-Fi. If not available, prefer to use 4G networks for both calling and browsing/data streaming. 2. Calling: Use wired headphones and keep the phone at least 1m away while calling. 3. Browsing/ Video Streaming: Keep device on a table/platform at least 50 cm away.
Wi-Fi Devices	1. Prefer smartphones over laptops for casual work such as e-mails/ browsing. 2. Keep smartphone/laptop on a table and operate from an arm's distance (50cm). 3. Avoid keeping smartphone in the pocket while it is connected to a Wi-Fi router. 4. Avoid keeping laptop on the lap while it is connected to a Wi-Fi router. 5. Wireless (Adhoc transfer) : Stay at least 1m away from both sender and receiver. 6. 4G Wireless Hotspot: Stay at least 2m away from the device while it is active.
Bluetooth Devices	1. Speakers: Keep speakers at least 25 cm away and connected smartphones at least 50 cm away. 2. Smartwatch: Avoid unless absolutely necessary. 3. Earphones: Avoid unless absolutely necessary.

exposure, there are numerous scientific studies, suggesting that even non-thermal effects pose a significant threat. These non-thermal effects are observed at several orders of magnitude of radiation lower than those of thermal effects. Along with the thermal and non-thermal effects, several other factors such as frequency, duration of exposure, pulse shaping, power level also contribute to health risks of EMR.

It has already been several years since the wireless-technologies have been deployed, meaning that the public has already been exposed to a lot of harmful EMR without their knowledge. It may be anticipated that this section of the population will suffer from many of the health hazards discussed in section V. If corrections are not made now, especially when the number of wireless devices are growing exponentially which leads to an exponential increase in public EMR exposure, the current and future public will be at even greater risks of both known and unknown health hazards. In particular, women, children and fetus are hypersensitive to EMR and special care must be taken to protect these groups from both short and long term exposure.

Smartphones, laptops, Wi-Fi routers, Wi-Fi Hotspots and Bluetooth devices such as speakers, earphones and smartwatches are the most common sources of exposure today. These devices are used extensively in very close proximity. Based on the discussion in section IV, it is clear that usage of mobile phones for calling or data streaming, using laptops and smartphones on Wi-Fi networks, using 4G wireless hotspots are especially dangerous. Exposure to radiation from one or two devices, such as a smartwatch on the wrist and a connected smartphone may result in high radiation levels only near the hand and pocket region, a cumulative and simultaneous exposure to several sources of EMR, such as laptop, smartphone, Wi-Fi router, Bluetooth earphones, smartwatch and speaker leads to dangerous levels of EMR all throughout the body and must be avoided. While it may take very long for the exposure levels of these devices to be corrected, the users can take some steps to minimize the risk of using these devices. A summary of the recommendations regarding usage of these devices is given in Table 7.

There are wired solutions in each of these use cases which can be adopted to greatly minimize EMR exposure. Using handsfree earphones to make phone-calls, using LAN cables instead of Wi-Fi, wired earphones, switching off Wi-Fi routers when not in use, maintaining a good distance from the wireless devices, are some of the measures to minimize exposure. A two-fold approach can be followed to minimize harm from EMR pollution. Firstly, measures can be taken to protect people from the already existing high levels of EMR. Second, proactive prevention techniques can be adopted in environments such as households, schools and hospitals to greatly minimize EMR exposure. These have been explained in detail in Section VI and VII of this paper.

Both individuals and governments must be aware of the fact that the current population has already been exposed to dangerous levels of radiation and the resulting adverse health effects may surface in people at any time. In this regard, proper planning and execution, both on governmental and individual levels is required to properly handle a breakout of EMR related health issues in large numbers of people in all areas of the world. Specifically, it must be noted that the radiation in 5G networks is suspected to increase by several folds. It will not only affect regions near cell towers and 5G devices but all indoor and outdoor environments in the region of coverage. Thus, almost all people in the area of coverage of 5G networks may be exposed to dangerous levels of EMR. Without thorough research and well-designed safety measures in place, wide-spread deployment of 5G networks could prove to be dangerous.

IX. CONCLUSION

People should be made aware that the EMR from using day to day cellular, Wi-Fi and Bluetooth devices are harmful to human health. The levels of radiation observed in most cases such as phone calls, internet browsing on laptops and smartphones, using wireless routers and hotspots, Bluetooth smartwatches and smartphones are unsafe when compared with radiations limits determined by medical bodies. According to the current medical literature, various adverse health effects from exposure to RF EMR have been well documented. For now, wireless technologies must be avoided as much as possible. New and innovative wired solutions which provide the same level of user-friendliness should be encouraged. Intervention of government and medical bodies with the main purpose of protecting human health is of utmost necessity to ensure good economic development without compromising the health of the population. Countries must adopt the guidelines suggested by medical bodies which take into account both thermal and non-thermal effects of EMR. At present, all individuals must take preventive and protective measures to protect themselves from harmful EMR exposure.

ACKNOWLEDGMENT

This research was made possible by NPRP10-1205-160012 grant from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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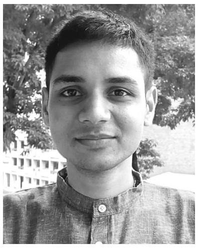
NAREN is currently pursuing the B.E. degree in electrical and electronics engineering and the M.Sc. degree (Hons.) in physics with the Birla Institute of Technology and Science, Pilani. He has completed projects on quark-gluon plasma, superconductivity, hardware security techniques in IoT, and electromagnetic radiation pollution. His other research interests include the IoT, industry 4.0, and security provisioning in V2G, UAV, and the medical IoT networks.

ANUBHAV ELHENCE is currently pursuing the B.E. degree in electronics and instrumentation engineering and the M.Sc. degree (Hons.) in physics with the Birla Institute of Technology and Science, Pilani. He was a part of the Japan-Asia Youth Exchange Program in science and was awarded an International Linkage Degree from Hiroshima University, Japan. His research interests include advanced brain signal processing, Internet of Things, and security in vehicular networks. He was a recipient of KVPY scholarship granted by the Department of Science and Technology, Government of India, and Sakura Science Scholarship granted by the Japanese Science and Technology Agency.



VINAY CHAMOLA received the B.E. degree in electrical and electronics engineering and the master's degree in communication engineering from the Birla Institute of Technology and Science, Pilani, India, in 2010 and 2013, respectively, and the Ph.D. degree in electrical and computer engineering from the National University of Singapore, Singapore, in 2016. In 2015, he was a Visiting Researcher with the Autonomous Networks Research Group, University of Southern California, Los Angeles, CA, USA. He is currently an Assistant Professor with the Department of Electrical and Electronics Engineering, BITS-Pilani, Pilani Campus. His research interests include green communications and networking, 5G network management, the Internet of Things, and blockchain.

MOHSEN GUIZANI (Fellow, IEEE) received the B.S. (Hons.) and M.S. degrees in electrical engineering and the M.S. and Ph.D. degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He served in different academic and administrative positions at the University of Idaho, Western Michigan University, University of West Florida, University of Missouri-Kansas City, University of Colorado-Boulder, and Syracuse University. He is currently a Professor with the Computer Science and Engineering Department, Qatar University, Qatar. He is the author of nine books and more than 600 publications in refereed journals and conferences. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grid. He is a Senior Member of ACM. He served as a member, Chair, and General Chair of a number of international conferences. Throughout his career, he received three teaching awards and four research awards. He also received the 2017 IEEE Communications Society WTC Recognition Award and the 2018 Ad-Hoc Technical Committee Recognition Award for his contribution to outstanding research in wireless communications and ad-hoc sensor networks. He was the Chair of the IEEE Communications Society Wireless Technical Committee and the Chair of the TAOS Technical Committee. He served as the IEEE Computer Society Distinguished Speaker and is currently the IEEE ComSoc Distinguished Lecturer. He is currently the Editor-in-Chief of the *IEEE Network Magazine*, serves on the editorial boards of several international technical journals, and the Founder and the Editor-in-Chief of *Wireless Communications and Mobile Computing* journal (Wiley). He guest edited a number of special issues in IEEE journals and magazines.