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MASTER'S THESIS

ANALYSIS OF THE IMPACT OF EMF EXPOSURE IN 5G DEPLOYMENTS

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ABSTRACT

5G or fifth-generation mobile network is being developed to meet the massive increase in data and connectivity, and it connects billions of devices via the internet of things. A significant advantage of 5G is the fast response time, also known as latency, which is delivered by faster connections and greater capacity. As 5G is using high frequencies such as above 6GHz, people are concerned about this electromagnetic field (EMF) exposure because it uses a large number of transmitters. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) issued guidelines to protect humans and the environment from radio frequency electro magnetic field (RF-EMF) exposure in the frequency range of 100kHz-300GHz. These constraints are expressed in terms of specific absorption rate (SAR), electric and magnetic field strength, and power density.

The goal of this thesis is to analyse the impact of EMF exposure in 5G deployment. The first step was to examine the EMF and its characteristics in general and in 5G in particular. Characteristics of 5G which are relevant to the electromagnetic field were then analyzed. The regulations related to human exposure to EMF were investigated globally, regionally, and in selected countries and compared with the key parameters including incident electric field strength, incident magnetic field strength, and incident power strength. To analyze the impact of the EMF in 5G two methods were used to assess EMF exposure: calculating the minimum distance and assessing the power density. Power density assessments were done for three different frequency bands (700MHz,1800MHz, and 3.5GHz), five different environmental scenarios (indoor hotspot, dense urban, rural, urban macro massive machine-type communications (mMTC), urban micro ultra-reliable low-latency communications (URLLC), and four different scenarios of a typical 5G network (indoor hotspot, dense urban, micro, micro remote radio head (RRH)), and by co-locating the three transmitters in the frequency bands 700MHz,1800MHz and 3.5GHz.

The results of the power density assessment in frequency bands 700MHz,1800Mhz, and 3.5GHz show that there is no EMF exposure near the transmitters. However, with the simulation results, we can see that there is an EMF exposure near the transmitter when considering various scenarios such as dense urban, rural, urban macro mMTC, urban micro URLLC, micro and micro remote radio head (RRH). With the simulation results of co-locating transmitters also we can see that there is also EMF exposure close to the transmitters. So, when deploying the 5G network in these environmental conditions, EMF regulations and limitations should be taken into greater account and deployment should be carried out to minimize this exposure. Thus, when planning the 5G network this exposed area should be included as a restricted area that the general public cannot access.

Keywords: 5G, Electromagnetic Field(EMF), Radiation Analysis, EMF exposure, Power Density

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FOREWORD

The primary focus of this thesis is to analyze the impact of EMF exposure in 5G deployment. During the thesis, it was very pleasing to work with my supervisors Adjunct Professor Marja Matinmikko-Blue and Professor of Practice Seppo Yrjölä at the Centre for Wireless Communication Radio Technology (CWC-RT) Research Unit at the University of Oulu. I am very grateful for having their continuous guidance and valuable support throughout my thesis.

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Hansika Dassanayake

LIST OF ABBREVIATIONS AND SYMBOLS

2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AL	Action Level
AP	Access Point
AM	Amplitude Modulation
AC	Alternating Current
BS	Base Station
CDF	Cumulative Distribution Function
EMF	Electromagnetic Field
EM	Electric and Magnetic
EMR	Electromagnetic Radiation
ELV	Exposure Limit Value
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile broadband
EU	Europe Union
FCC	Federal Communication Commission
FWA	Fixed Wireless Access
FM	Frequency Modulations
HSE	Health and Safety Executive
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
IC	Contact Current
J	Current Density
LOS	Line of Sight
LTE	Long Term Evolution
MPE	Maximum Permissible Exposure
MSIT	Ministry of Science and ICT Korea
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
mMTC	Massive machine-to-machine communications
mMIMO	Massive MIMO
NIR	non-ionization radiation
NLOS	Non-Line of Sight
PHE	Public Health England
PD	Power Density
QoS	Quality of Service
RF	Radio Frequency
RRA	National Radio Research Agency

RRH	Remote Radio Head
RMS	Root Mean Square
S	Power Density
SAR	Specific Absorption Rate
STUK	The radiation and Nuclear Safety Authority
SDR	Software Define Radio
SA	specific absorption
Tx	Transmitter
uRLLC	Ultra-reliable low latency communications
UV	Ultraviolet
UMa	Urban Macrocell
UM-S.C	Urban Microcell Street Canyon
Umi-O.S	Urban Micro Open Square
USA	United States
UE	User Equipment
UK	United Kindom

B	Magnetic Flux Density
C_a	Single gNB's coverage area
d	Distance Between the transmitter and the mobile station
$d_{\text{far-field}}$	Far-field distance
E	Electric Field Strength
E_{inc}	Incident E-Field Strength
$EIRP$	effective Isotropic Radiation Power
f	Operating Frequency
$FSPL(f,1m)$	Free Space Path loss
G_T	Transmitter Antenna Gain
G_{RX}	Receiver Antenna Gain
G_T	Transmitter gain
H	Magnetic Field Strength
H_{inc}	Incident H-Field Strength
IL	Limb Current
IC	Contact Current
J	Current Density
L_{TX}	Losses
P_t	Transmitter power
P_D	Power Density
P_T	Transmitter Antenna Power
$PL^{CI}(f,d)$	Path Loss
P_{RX}	Power Received by the mobile station
P_{avg}	Spatially Averaged Power Densities
R	Minimum distance between the transmitter and the general public
S	Spatial Peak Equivalent Power Density
S_{ab}	Absorbed Power Density
S	Power Density
S_{inc}	Incident Power Density
S_q	Total Surface area
X_{σ}^{CI}	Shadow Fading (SF)
λ	Wave Length
Γ	Reflection Coefficient
σ	Standard Deviation

1. INTRODUCTION

1.1. Background of the Research

EMF Radiation is a moving electrical and magnetic field that travels in the form of an electromagnetic field through a medium (EMF). Air is the most common medium for electromagnetic propagation, but it can also occur in other media such as water or vacuum. EMF can be generated by using any electrical or electronic device, such as a television, computer, hair dryer, mobile phone, and so on. The electromagnetic field, on the other hand, is the desired product in wireless networks because it is responsible for transmitting information from an antenna to mobile phones and laptops and vice versa. With the introduction of new generations of mobile networks such as 2G, 3G, 4G, and 5G[1], it has been questioned whether there are health and safety concerns associated with the electromagnetic field radiation (EMF) emitted by mobile wireless networks. When considering the impact of EMF, it is only possible for EMF to raise body temperature. There is no evidence that the EMF caused a brain tumor or cancer. Because of rising body temperatures, there are regulations and guidelines in place to limit EMF exposure. These guidelines are divided into two categories: general public and occupational (workers). By considering Globally, guidelines were issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [3].

Base stations transmit and receive radio waves to connect users of mobile phones and other devices to mobile communication networks. Radio waves from base station antennas lose strength quickly as distance increases, and the levels to which the general public is typically exposed are low in comparison to levels at other locations. Radio frequency (RF) exposure levels during a phone call or while sending and receiving data are proportional to the actual output power of a mobile phone. When used as intended, the output power of a mobile phone is typically significantly lower than its maximum output power due to adaptive power control[2]. The output power of a mobile phone, as well as the intensity of the exposure, can vary depending on a variety of factors, including technology, location, transit, and phone usage[2]. Because of the greater distance between the nearest base station, the output power of mobile phones used in rural areas is greater than in urban areas[2]. 5G technology uses three frequency bands: sub-1 GHz, 1-6 GHz, and above 6 GHz[1]. High-frequency bands above 24GHz [2] are referred to as millimeter-wave bands and, they cannot travel well through obstacles. However, they can be absorbed by plants or rain. To address this issue, 5G technology employs small cells. As a result, a large number of base stations are used here, and those base stations are very close to one another. As a result of a large number of antennas in 5G base stations, people are concerned about EMF exposure from them.

When considering the EMF exposure from the base station to the general public and occupational, the regulations and limitations for the general public and occupational are always considered globally, regionally, and country-wise. Most countries take into account the ICNIPR regulation, which describes the protection of humans exposed to radiofrequency electromagnetic fields (RF-EMF) within the frequency range from 100kHz to 300GHz. Specific absorption rate (SAR), electric and magnetic field strength, and power density define these limits. Many countries, including the majority of EU countries, accepted the ICNIPR guidelines. In addition to the ICNIRP regulation, the European Council issued an EMF exposure limit for EU countries, including Finland. The radiation and Nuclear Safety Authority (STUK) is in charge of nuclear and radiation safety in Finland and issued regulations to protect people and the environment from RF-EMF exposure. In addition, the

United Kingdom's Health and Safety Executive (HSE) and the United States Federal Communication Commission (FCC) published regulations to minimize EMF exposure.

When deploying the 5G network, EMF analysis must be performed in accordance with the guidelines and regulations limits. Before placing the transmitter antenna, the minimum distance between the transmitter and the general public should be considered, and the antenna location should be determined accordingly. For example, when deploying in urban and residential areas, base station antennas are typically placed on rooftops or at a sufficient distance from neighboring buildings. Base stations in small cells are located on the street level to provide dedicated coverage. The transmitters are placed on a high ceiling roof or a roof nearly 10m high in the indoor scenario. On the other hand, in an indoor scenario, there may be numerous obstacles, necessitating the placement of additional transmitters to transmit data through these obstacles. As a result, the constraints imposed by EMF regulations must be carefully considered when deploying the 5G network and thereafter while operating 5G equipment. This thesis investigates how EMF regulations affect the deployment of 5G networks. Following research, problems within the period are considered, and simulations are performed to answer them.

1.2. Research Problem

Following research questions were analyzed during the thesis.

- How is EMF defined and evaluated in general and specifically in 5G?
- What are the characteristics of 5G which are relevant to the EMF?
- What are the regulations related to Human Exposure to Electromagnetic Fields (EMF) in 5G in selected countries?
- How do regulations and limitations impact the 5G deployment?

To understand the concept of EMF in 5G and its characteristics, as a first step of the research EMF is defined and evaluated in general and specifically in 5G. The characteristics of 5G that are relevant to the electromagnetic field in 5G were then analyzed. Then, with their limit values, compare the EMF regulations globally, regionally, and in specific countries. Finally, using MATLAB, we analyzed the impact of EMF in 5G deployment for the general public and discussed the impact in relation to the regulatory limit values.

1.3. Structure of the Thesis

This thesis is mainly divided into five chapters. Each chapter comprises a specific area related to this research. The organization of the thesis is as follows.

Chapter 2 - Includes the background knowledge required to understand the main concepts of this research.

Chapter 3 - In this chapter, EMF regulations are discussed globally, regionally and country-specific.

Chapter 4 – Under this section, the EMF in 5G and related literature on this topic is presented.

Chapter 5 – In this chapter system model and simulation results are discussed.

2. THEORETICAL BACKGROUND

This chapter describes the background knowledge required to understand the main concepts of this research.

2.1. Electromagnetic Radiation

In classical physics, electromagnetic radiation is defined as the movement of energy through free space or a solid medium at the speed of light in the form of electric and magnetic fields, which combine to generate electromagnetic waves such as radio waves, and visible light, and gamma rays. During the propagation of a wave, time-varying electric and magnetic fields are linked to one another at right angles and perpendicular to the direction of the motion. The intensity of an electromagnetic wave and the frequency v of the time fluctuation of the electric and magnetic fields are the characteristics of an electromagnetic wave [5].

Electromagnetic radiation (EMR) can be defined as the flow of photons through space [5]. In a vacuum, electromagnetic radiation is propagating at the speed of light and normally in a straight line. Also, this EMR is emitted and absorbed by charged particles. An electromagnetic wave has both Electric and Magnetic field components that oscillate in a phase to one another and perpendicular to each other. Also, perpendicular to the direction of energy and wave propagation.

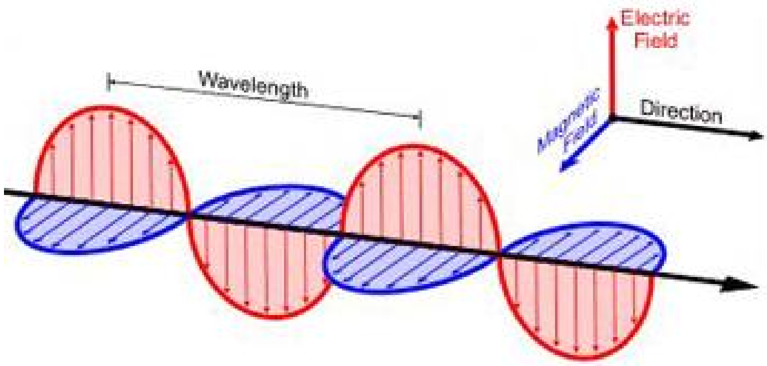

Figure 1 Propagation of Electromagnetic wave [6]

Electric and Magnetic fields are the main element of the electromagnetic spectrum, and those elements are extending from the static and magnetic field over radio frequency (RF), infrared radiation, and visible lights to X and gamma-rays. The electromagnetic spectrum is shown in the following figure.

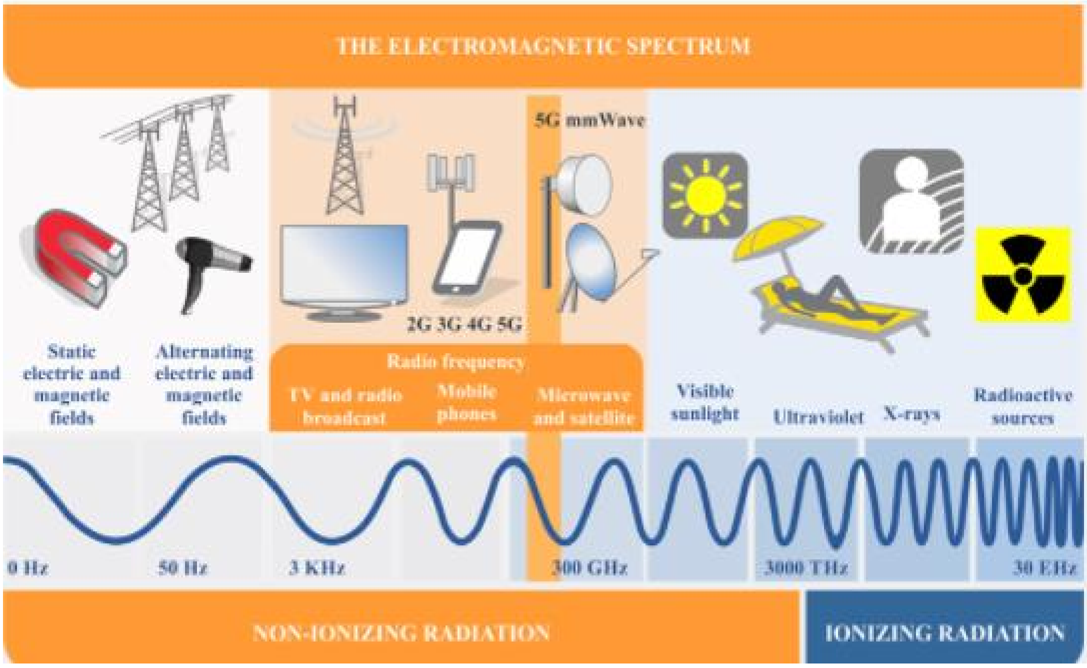

Figure 2 Electromagnetic Spectrum [7]

Ionizing radiation is electromagnetic radiation that is above the Ultraviolet (UV) spectrum. That is because it has enough energy to cause changes in atoms by ionizing. X-rays and gamma rays are common forms of ionizing radiation. The frequency bands above 2900THz are occurring in these ionizing radiations.

Non-ionizing radiations are electromagnetic energy that is below UV bands and the RF field is such non-ionizing radiations. That is because they have a lack of energy to release energy to ionize or effect changes in atom structure.

The electromagnetic field is a property of space produced by the motion of an electric charge. Electric fields are created by differences in voltage [8]. In the higher voltage, the resultant field is very strong. When the electric current flows, magnetic fields are created and the greater the current magnetic field is strong. But the electric field is excited even though there is no current flowing. If there is no current flowing the strength of the magnetic field is vary with power consumption [8]. But the strength of the electric field will be constant.

In the surrounding space, a stationary charge is producing only an electric field. But if the charge is moving it produced a magnetic field also. By changing the magnetic field, an electric field can be produced. The electromagnetic field is produced by the mutual interaction of these electric and magnetic fields. This electromagnetic field can be defined as an area of moving Electrical and Magnetic (EM) field through a medium [9] such as air and those can be propagated through water or vacuum.

Electromagnetic fields are produced everywhere in the environment. But those are invisible to the human eyes. when considering the natural sources of electromagnetic fields, electric fields are mainly occurred in between the ground and the upper layers of the atmosphere. They are mainly caused by the radiation of the sun and by solar winds [10]. When thunderstorms are associated with the local build-up of the electric charges in the atmosphere these natural electric fields can be produced. The earth's magnetic field causes a compass needle to orient in a North-South direction [10] and this will help navigation for the birds and fish.

Human-made electromagnetic fields can be produced by electrical appliances and radio communication devices. When considering the electrical appliances electromagnetic fields can be generated by vacuum cleaners, hairdryers, and refrigerators. For radio communication devices there are lots of devices such as Amplitude Modulation(AM)/ Frequency Modulation(FM) radio and television, emergency service radio (police, fire, and ambulance), air traffic control, cordless phone, remote controls, mobile phones, and Wi-Fi phones.

2.2. Overview of 5G

5G is the 5th generation of mobile networks, a significant evolution of today's 4G Long Term Evolution (LTE) networks [11]. 5G has been developed to accommodate the extremely rapid expansion in data and connectivity experienced by today's modern civilization, as well as the internet of things, which includes billions of connected objects, and the innovations of tomorrow [11]. 5G wireless networks will first coexist alongside current 4G wireless networks before transitioning to standalone networks in subsequent releases and coverage extensions.

To satisfy today's modern society's massive increase in data and connectivity, 5G has been developed and it targets a higher data capacity than 4G by allowing a higher density of mobile broadband users and supporting device-to-device, ultra-reliable, and massive machine communication. With connecting billions of connected devices by the internet of things it meets the very large growth in data and connectivity of today’s modern society as well as tomorrow’s innovations [11]. When compared with the other wireless networks, 5G is the fast response time referred to as latency. The latency of the 3G network is 100 milliseconds, 4G is around 30 milliseconds and 5G has a minimum value which is 1 millisecond. When considering the use cases of 5G, there are three major use cases. Those are massive machine-to-machine communications (mMTC), Ultra-reliable low latency communications(uRLLC), and enhanced mobile broadband(eMBB) [11].

Ultra-Reliable Low Latency Communications(URLLC):

This is used for the real-time control of device industrial robotics, vehicle-vehicle communication, and safety system. Also, for medical care, procedures and treatment can be done using 5G [11]. It enables ultra-responsive connectivity and has a latency of less than 1 ms at the air interface. Additionally, it supports low to medium data transfer rates (50 kbps to 10 Mbps) and high-speed mobility [12].

Enhanced Mobile Broadband(eMBB):

It has connected the world, it provides much faster data speeds and greater capacity. It can be used for outdoor broadcast applications without broadcast vans, and greater connectivity for the moving people [11]. eMBB's peak data rate is between 10 and 20 Gbps, while its minimum data rate is 100Mbps. Additionally, it boosts traffic capacity by a factor of 100. Supports large and small cells, as well as a high mobility of about 500 kilometers per hour. Additionally, it increases network energy savings by a factor of 100 [12].

Massive Machine-Type Communications(mMTC):

This is the case when a large number of linked devices transmit a little amount of non-delay sensitive data. Typically, these devices are inexpensive, consume little power, and have long battery life. These devices are many and are designed to serve applications in logistics, industry, agriculture, and remote sensing.

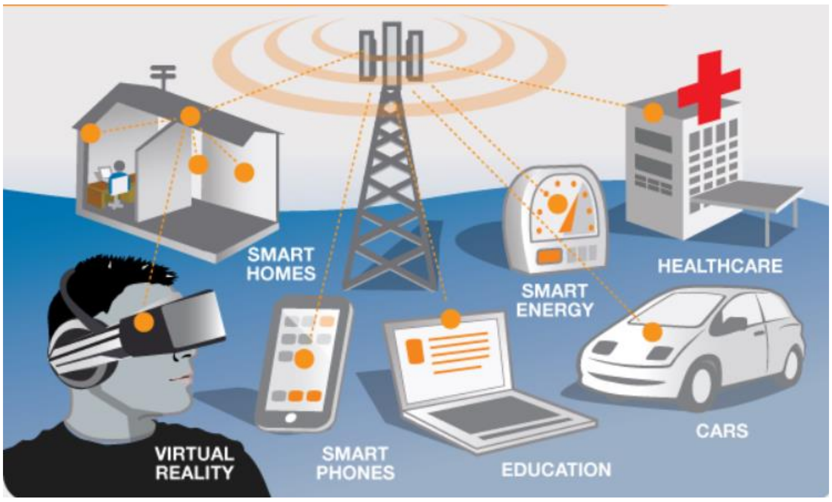

Figure 3 Connected community of 5G [11]

5G massive Multiple Input Multiple Output (MIMO) antennas are similar to existing 3G and 4G base station antennas [13], which contain a large number of antenna elements to simultaneously send and receive data. The benefit of using massive Multiple Input Multiple Output (mMIMO) is that more individuals can connect to the network at the same time while maintaining excellent throughput. The physical dimensions of the mMIMO antenna are similar to that of a 4G antenna, however, it operates at a higher frequency.

mMIMO base station antennas direct signals to users and devices by utilizing beam steering and beamforming technology. As a result, the signals are not directed in all directions. The beam steering technology employs advanced signal processing algorithms to find the ideal region for the radio transmission. As a result, interference is reduced, and efficiency is increased.

5G is using three key frequency ranges and therefore it can deliver wide coverage for the service. Those frequency bands are sub-1 GHz, 1-6 GHz, and above 6 GHz [1].

- Sub-1 GHz support coverage across urban, suburban, and rural areas. Also, by better in-building coverage it supports IoT services.
- 1GHz to 6 GHz deals with a good mixture of coverage and capacity benefits.
- Above 6 GHz is used for the ultra-high broadband speeds planned for 5G.

5G frequency bands are shown in the following figure.

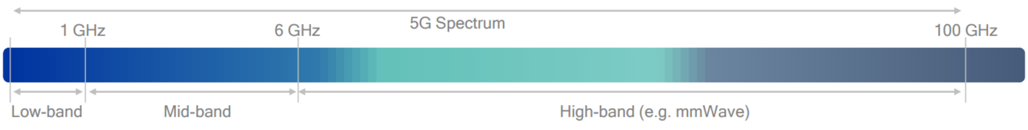

Figure 4 Frequency Band in 5G [11]

5G needs low bands for coverage, medium bands for faster speeds covering suitable areas, and high-frequency bands for highest speeds [14].

The lower frequency band exhibits the best propagation characteristics, allowing data to travel further by following the inverse square law. Additionally, it is capable of traveling through physical obstacles. Therefore, the lower frequency range could be used to support data transmission at a slower rate. As an example of large-scale IoT applications requiring hourly or even daily reporting, such as those in the water industry. The lower frequency range is more compatible with remote, rural areas where Fixed Wireless Access (FWA) is deployed [15].

The mid and high-frequency band has high data speed and latency. But it has poor propagation properties. It is not possible for the waves in this band to travel long distances as well as pass-through walls, physical obstacles, and rain. 3.6GHz is used for urban and wider coverage such as mobile Gigabite society and smart cities. 26GHz is used for the hotspot coverage and Fixed Wireless Access (FWA) with small cells in railway stations, sports events, and smart factories [16].

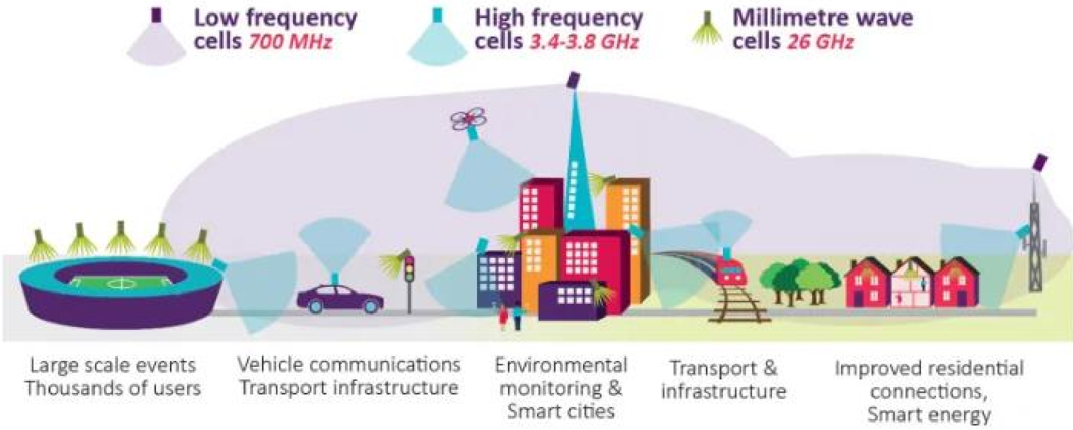

Figure 5 5G Frequency Band Usage [14]

2.3. Type of Cells

Small cells will be a key element of 5G networks, particularly at new millimeter wave (mm Wave) frequencies with extremely small connection ranges. To provide a continuous connection, small cells will be clustered according to the locations of users who require connectivity, complementing the macro network's wide-area coverage. In most cases, the range of a Small Cell is less than one kilometer, while that of a Macro Cell might be as much as many tens of kilometers or more. These 5G nodes are capable of performing many of the same functions as traditional base stations. When considering the size of this small cell it is about the size of a pizza box and it enables mm Wave frequencies to transmit the data with high-speed connectivity and handle the high data rates [17]. Due to the limited range of 5G transmitters, several small-cell antennas are required to deliver the services promised by 5G, and signals are transmitted by using the MIMO, beamforming, and mm Wave. Low power transmitting stations are deployed by using these small cells and therefore those stations can be mounted on walls for indoor applications and lamp posts for outdoor applications [17].

Wireless cells are classified into Macro Cells, Micro Cells, Pico Cells, and Femtocells based on their radius and transmit (Tx) power levels. The actual cell size is determined not only by the Tx power of the cell but also by the antenna's position and height, as well as the deployment environment, such as indoor or outdoor, rural or urban. Depending on the deployment environment, the type of communications, and the quality of services, any of the cells may be a better candidate than the others.

Table 1 Type of Cell with their cell radius and number of user equipment [17]

Cell Type	Cell Radius	No. of UEs
Macro	>1km	1200
Micro	250m – 1km	400
Pico	100m-300m	64-256
Femto	10m-50m	10-50

Macrocell transmits and receives radio signals by using MIMO. It is operating the antenna which is mounted on a tower or 5G transmitter mast which is usually high 50 to 20 feet. While reducing latency or response time it enables to connect the billions of devices.

According to the above table, 5G microcell coverage is less than 1km. As the microcell towers are small, they can be based on the lamp posts. The main advantage of this microcell is its energy efficiency.

Pico cells are deployed for the small area coverage such as outdoor public venues and hotspots, especially in capacity-starved locations such as stadiums, airports, and shopping malls. Transmission cost is reduced by the picocells as they use the lower Tx power than microcells.

Femtocells can be deployed more efficiently based on the user's needs and it is usually privately owned, unlike micro or picocells. A Femtocell covers very small areas (10-50m) and is commonly used inside homes and offices. Within a femtocell network, there have no line-of-sight constraints. But it can support a limited number of users and ranges just over 30 feet. The infrastructural cost of the Femtocell can be saved as it connects to the existing residential backhaul links.

2.4. Effect of RF-EMF in 5G

The electromagnetic field in 5G is described in this section. Throughout the COVID 19 epidemic, widespread misinformation regarding the EMF in 5G was propagated. Thus, it is important to understand what this EMF in 5G is.

After being accompanied with much research there is no harmful effect linked with exposure to wireless technologies. Increasing the body temperature by heating tissues is the main mechanism of interaction between the RF-EMF and the human body [15]. This is known as a thermal effect. RF exposure by the current technologies there is a negligible temperature rising in the human body. But when the frequency is increasing there is less penetration into the body tissues. Therefore, the absorption of the energy is limited to the human body surface such as the skin and eye.

The demand for a very high data rate in 5G necessitates a receiver with a higher signal power. For example, according to a recent link budget study [19], the needed received power increases from -65 to -37.5 dBm as the data rate increases from 1 to 6 Gbps. Such an increase in signal strength received at the user's end raises concerns about the quantity of EMF energy placed on the human user [20][21][22].

At frequencies above 6GHz, there can be two reasons for concern about the EMF exposure to a human being. First, at the base station, it uses a large number of transmitters. Secondly, it uses narrow beams at high frequencies as a solution for higher attenuation. Furthermore, 5G is using small cell network and it uses the access points (Ap)/Base Stations (BS) to serve a small geographical area. Because of this, those are located very close to humans. Also, it deployed a large number of APs/BSs and because of that, there is a higher chance to expose EMF to humans which are generated by downlink.

But there is some misinformation spread related to this 5G EMF exposure in the COVID 19 pandemic and it was fueled by social media and has caused a spate of an incident in different countries. Some countries reported that the people are burning or destruction of several antenna masts as well as the harassment of telecommunication technicians [18].

Some people are concerned that increasing the number of antennas would increase EMF exposure. The European Commission takes public health protection extremely seriously and guarantees that any emissions are subject to stringent safeguards. 5G networks will utilize small cells with lower power levels and thus lesser EMF exposure than current 4G networks' huge cells. According to a recent European Commission research, while total exposure levels may increase slightly in metropolitan areas where 5G will be deployed alongside 4G towers, they will remain well below safe levels, which are 50 times lower than the levels at which health impacts are possible. As 4G antennas go out of use, exposure levels will decrease [23].

3. GENERAL REGULATIONS FOR ELECTROMAGNETIC FIELD

This chapter describes the global regulations for electromagnetic fields. Under global regulations, ICNIRP regulations were discussed according to the frequency bands. Then considering regional regulations, the European commission's regulation was discussed. Regarding country-specific regulations, Finland, the United Kingdom, the United States of America, and South Korea were discussed.

Numerous national and international documents provide the safety levels of exposure to EMFs for humans. These documents consist of basic limits and reference levels, two-tired exposure limits, averaging times, and separate consideration for exposure to low-frequencies and high-frequency fields [24]. International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) are two international organizations that established the exposure guidelines and exposure levels. Those guidelines are defined in terms of specific absorption rate (SAR), electric and magnetic field strength, and power density in the 5G frequency band to protect against all potential harmful health effects RF-EMF by 5G technologies. But for some countries, these exposure limits are different and more restrictive. Finland, the United Kingdom, the United States, and some other countries have their regulation and exposure limits values for protecting the people from the effect of RF-EMF.

Most regulations are in terms of reference levels and basic restrictions. The basic limits are concerned with the fundamental quantities that determine the physiological reaction of the human body to electromagnetic fields. When there is a body present in the field, there are some basic restrictions that apply. The specific absorption rate (SAR), the specific absorption (SA), and the current density are the basic limits for human exposure to ionizing radiation [24]. Most of the documents provide the guidelines reference level for the electric field, magnetic field, and power densities as difficult to measure the basic quantities directly.

3.1. Global Regulations: INCIRP Guidelines for Electromagnetic Fields

The regulation which was issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) intends to protect the people and the environment through non-ionization radiation (NIR) [18]. To provide the exposure restriction values they used different kinds of factors such as age, sex, tissue temperature, temperature, humidity, clothing, etc [3]. These limits were established after a thorough evaluation of the scientific literature was conducted to identify potentially dangerous effects and the thresholds at which they occur. The interruption of ongoing behaviors is linked with an increase in body temperature in the presence of electromagnetic fields of the potentially detrimental biological consequences of electromagnetic fields. In part, this was due to a scarcity of trustworthy data on chronic RF energy exposure, hence the majority of the research focused on short-term (less than an hour) RF energy exposure. When operating within the ICNIRP restrictions, the average times are short (6 – 30 minutes) and reflect thermal considerations [25].

The International Commission on Nuclear and Radiological Protection (ICNIRP) establishes exposure limits using a variety of criteria over a wide range of frequencies. One such statistic is the "Specific energy absorption rate" (SAR), which is defined as the power per unit mass absorbed(W/kg). Under the frequency range of 6 GHz, where EMF can penetrate deeply into tissue, this is an extremely valuable statistic. Because EMF above 6 GHz is absorbed more superficially, it is important to define exposure in terms of the density of absorbed power over the area(W/m2) when the frequency is greater than 6 GHz. This statistic is referred to as "power density" in colloquial terms. Power density is the only statistic used above 10 GHz, whereas SAR is the only metric used below 10 GHz for the entire body, limbs, and head [26]

The guideline made regulations for those who are exposed at work (Occupationally) and those who are exposed as members of the general public and the guideline are in terms of basic restriction and reference level. Occupational exposure limits apply to adult individuals exposed under controlled conditions associated with their occupational duties [26]. They are trained to protect themselves by taking proper precautions from the radiofrequency EMF risks. Individuals of all ages who are not aware of, or are unable to regulate, their exposure to EMFs are subject to the general public exposure restrictions. These discrepancies indicate that stricter limitations for the general public are required, as members of the general public are not trained to mitigate harm and may not have the necessary resources to do such a task.

- **Specific Absorption Rate(SAR)**: Specific Energy Absorption rate (SAR) is a measure of how much RF energy is absorbed by tissues in the human body [26]. Because of adaptive power control and the connection back to the mobile network, the SAR emitted by a mobile phone varies significantly throughout the operation. To effectively compare individual mobile phone models, a maximum SAR value does not provide significant information regarding the amount of RF exposure under typical usage conditions. The exposure level depends on the distance between the person and the mobile phone as well as the amount of power the mobile transmits. The exposure depends on the distance between the person and the mobile devices [26], distance from the base station, obstacles between the base station and the user, and the service which the user is using.
- **Specific Absorption(SA)**: The quotient of incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) with a particular density (m) is known as specific absorption. It is expressed in joules pwe kilogram(J/Kg).

$$\text{Specific Absorption(SA)} = \frac{dW}{dm} = \frac{1}{\rho_m}\frac{dW}{dV} \quad (1)$$

- **Head and Torso:** Comprises the head, eye, pinna, abdomen, back, thorax, and pelvis.
- **Limbs:** Comprises the arm, forearm, hand, thigh, leg, and foot.
- **Absorbed Power Density(S_{ab}):** It is a rate of absorption of energy(W) per cubic meter.
- **General Public:** In the guideline, all non-workers are defined as the general public. Individuals of all ages and health statuses are exposed to the general public in unmanaged conditions, and this includes children and pregnant women among other people.
- **Power Density(S):** Power flux-density is defined as the amount of power per unit area that is normal to the direction of electromagnetic wave propagation. It is commonly given in units of watts per square meter (W/m^2). When considering the plane wave, the inherent impedance of free space, Z_0= 377 or $120\pi\Omega$, determines the relationship between power flux-density, electric field strength (E), and magnetic field strength (H).

$$S_{eq} = \frac{E^2}{z_0} = Z_0H^2 = EH$$

Table 2 Basic Restrictions for EMF exposure from 100kHz to 300GHz [3]

Exposure Scenario	Frequency Range	Whole-body average SAR (Wkg^{-1})	Local Head/Torso SAR(Wkg^{-1})	Local Limb SAR(Wkg^{-1})	Local S_{ab}(Wm^{-1})
Occupational	100kHz-6GHz	0.4	10	20	NA
	>6GHz-300GHz	0.4	NA	NA	100
General Public	100kHz-6GHz	0.08	2	4	NA
	>6GHz-300GHz	0.08	NA	NA	20

In the above graph, the whole-body average SAR is averaged over 30 minutes, and local SAR and S_{ab} exposures are averaged over 6 minutes. Also, when calculating the local SAR, it is averaged over 10-g cubic mass and local S_{ab} is averaged over a square $4cm^2$ surface area of the body [3].

Reference levels can be used to provide a means of demonstrating compliance using quantities that are more easily assessed than basic restrictions. These reference levels are derived by a combination of computational and measurement studies. Reference levels for exposure averaged over 30 min, and the whole body to EMF from 100 kHz to 300 GHz are shown in the following table.

Table 3 Reference Level for EMF exposure from 100kHz to 300GHz (averaged over 30 min) [3]

Exposure Scenario	Frequency Range	Incident E-field strength(E_{inc})(Vm^{-1})	Incident H-field strength(H_{inc})(Am^{-1})	Incident Power density S_{inc}(Wm^{-1})
Occupational	0.1-30MHz	$660/f_M^{0.7}$	$4.9/f_M$	N A
	>30-400MHz	61	0.16	10
	>400-2000MHz	$3f_M^{0.5}$	$0.008f_M^{0.5}$	$f_{M/40}$
	>2-300GHz	NA	NA	50
General Public	0.1-30MHz	$300/f_M0.7$	$2.2/f_M$	NA
	>30-400MHz	27.7	0.073	2
	>400-2000MHz	$1.375f_M^{0.5}$	$0.0037f_M^{0.5}$	$F_M/200$
	>2-300GHz	NA	NA	10

3.2. European Council Regulations

The Council of the European Union published the limitation of exposure of the general public to electromagnetic fields (0Hz to 300GHz) by their Council Recommendation of 12 July 1999 [27]. To apply limits based on the assessment of potential health consequences of electromagnetic fields, it is necessary to distinguish between basic restrictions and reference levels of exposure.

When considering the basic restrictions, the restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields are defined as those that are based on recognized health consequences and biological factors. The physical variables used to quantify these constraints vary depending on the frequency of the field and include magnetic flux density (B), current density (J), specific energy absorption rate (SAR), and power density (S). Individuals who have been exposed to magnetic fields can easily be assessed for magnetic flux density and power density. Reference levels are offered for practical exposure assessment reasons to identify whether or not the fundamental limits are likely to be violated in the future. In some cases, reference levels are obtained from appropriate basic constraints through the use of measurements and/or computational approaches, whereas in other cases, reference levels are derived from perception and detrimental indirect consequences of EMF exposure. Electric field strength (E), magnetic field strength (H), magnetic flux density (B), power density (S), and limb current(IL) are the quantities of reference level [26]. The quantities such as contact current (IC) and, in the case of pulsed fields, specific energy absorption(SA) are those that deal with perception and other indirect effects.

The quantities which are commonly used in the context of EMF exposure are as follows.

- **Contact current (IC)** between a person and an object is expressed in amperes (A). A conductive object in an electric field can be charged by the field [27].
- **Current density (J)** is defined as the current flowing through a unit cross-section perpendicular to its direction in a volume conductor such as the human body or part of it, expressed in amperes per square meter (A/m^2) [27].
- **Electric field strength** is a vector quantity (E) that corresponds to the force exerted on a charged particle regardless of its motion in space. It is expressed in volts per meter (V/m) [27].
- **Magnetic field strength** is a vector quantity (H), which, together with the magnetic flux density, specifies a magnetic field at any point in space. It is expressed in amperes per meter (A/m) [27].
- **Magnetic flux density** is a vector quantity (B), resulting in a force that acts on moving charges, it is expressed in teslas (T). In free space and biological materials, magnetic flux density and magnetic field strength can be interchanged using the equivalence $1\ A\ m^{-1} = 4\pi\ 10^{-7}\ T$ [27].
- **Power density (S)** is the appropriate quantity used for very high frequencies, where the depth of penetration in the body is low. It is the radiant power incident perpendicular to a surface, divided by the area of the surface, and is expressed in watts per square meter (W/m^2) [27].
- **Specific energy absorption (SA)** is defined as the energy absorbed per unit mass of biological tissue, expressed in joules per kilogram (J/kg). This recommendation is used for limiting the non-thermal effects of pulsed microwave radiation [27].
- **Specific energy absorption rate (SAR)** averaged over the whole body or parts of the body, is defined as the rate at which energy is absorbed per unit mass of body tissue

and is expressed in watts per kilogram (W/kg) Whole-body SAR is a widely accepted measure for relating adverse thermal effects to RF exposure. Besides the whole-body average SAR, local SAR values are necessary to evaluate and limit excessive energy deposition in small parts of the body resulting from special exposure conditions. Examples of such conditions are a grounded individual exposed to RF in the low MHz range and individuals exposed in the near field of an antenna [27].

Table 4 Basic Restrictions for electric, magnetic and electromagnetic fields (0Hz to 300GHz) [27]

Frequency Range	Magnetix Flux Density(mT)	Current density (mA/m^2)(rms)	Whole bodyaverage SAR(W/kg)	Localised SAR (head and trunk)(W/kg)	Localised SAR (Limbs)(W/kg)	Power density (W/m^2)
0 Hz	40	-	-	-	-	-
>0-1Hz	-	8	-	-	-	-
1-4Hz	-	8/f	-	-	-	-
4-1000Hz	-	2	-	-	-	-
1000Hz-100kHz	-	f/500	-	-	-	-
100kHz-10MHz	-	f/500	0.08	2	4	-
10MHz-10GHz	-	-	0.08	2	4	-
10-300GHz	-	-	-	-	-	10

As per the above table, the operating frequencies are in Hz. When considering the frequencies between 0-1Hz, the restriction values are given for magnetic flux density and current density to prevent the effects on the cardiovascular and central nervous systems [27]. Frequencies between 1Hz and 10MHz restriction values are provided for current density to the effect on nervous system functions [27]. To prevent the whole-body heat stress and excessive localized heating of the tissues, the restriction value of SAR is provided for the frequencies between 100kHz and 10GHz. Also, the power density is provided to prevent the heating in tissue at the near body surface for the frequency range 10GHz to 300GHz [27].

The below table shows the reference level for electric, magnetic and electromagnetic fields for the frequencies between 0Hz to 300GHz. By using the reference levels, it is easy to compare the measured values. If the reassured values are greater than the reference levels, it does not always follow that the basic restrictions have been exceeded. If that happens, an assessment should be made as to whether exposure levels are below the minimum permissible values of basic restrictions

Table 5 Reference Level for electric, magnetic and electromagnetic fields (0Hz to 300GHz) [27]

Frequency Range	E-Field strength (V/m)	H-Field Strength(A/m)	B-Field (μT)	Equivalent plane wave power density (W/m^2)
0-1 Hz	-	3.2×10^4	4×10^4	-
1-8 Hz	10000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	-
8-25 Hz	10000	4000/f	5000/f	-
0.025-0.8 kHz	250/f	4/f	5/f	-
0.8-3 kHz	250/f	5	6.25	-
3-150 kHz	87	5	6.25	-
0.15-1 MHz	87	0.73/f	0.92/f	-
1-10 MHz	$87/f^{1/2}$	0.73/f	0.92/f	-
10-400 MHz	28	0.073/f	0.092/f	2
400-2000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	f/200
2-300 GHz	61	0.16	0.20	10

3.3. Country-Specific Regulations

3.3.1. Finland EMF Regulations

In Finland, the Finnish Radiation and Nuclear Safety Authority(STUK) regulates radiation and nuclear safety. The mission of the STUK is to protect people, society, the environment, and future generations from the harmful effects of radiation on the environment and people. As part of the radiation regulations, exposure limit values have been established to assure the radiation safety of mobile networks. They are founded on the most recent scientific evidence and encompass all existing and future frequencies, as well as any additional frequencies that may be introduced into the 5G network. Exposure limits are designed to protect against the health consequences of both short- and long-term exposure. As a result, there is no need for consumers to be concerned about radiation exposure generated by the 5G network.

The Ministry of Social Affairs and Health established population exposure limit values and action levels for electromagnetic fields, which were codified in a decree. They do so following the Council of the European Union's advice, which is in effect in the majority of European countries. When it comes to setting limit settings, great attention has been taken. Radiation-induced tissue warming is the sole consequence of radiofrequency radiation that has been scientifically verified, resulting in a substantial safety margin between the exposure limit and potentially dangerous tissue warming.

The regulation is based on two sets of values related to EMFs: Action Level(AL) and Exposure Limit Value(ELV) [28]. Based on the guidelines of the International Commission on Non-Ionizing Radiation Protection, those physical quantities have been calculated (ICNIRP). ELVs are the legal restrictions on the exposure of employees to electromagnetic fields (EMFs), and they are primarily concerned with the levels of exposure to EMFs that occur within the body. Direct measurement of these is frequently impossible or extremely complex and expensive. This is why a different set of values, known as ALs, has been developed that corresponds to quantities that can be measured more quickly.

Action Levels have two main purposes. It is possible to utilize specific ALs to establish that EMF levels are below specific ELVs and indirect-effect ALs are not tied to a particular

ELV instead they detail the EMF levels above which particular indirect effects may take place [25]. ELVs are limits that have been established to protect employees from the health and sensory consequences of electromagnetic fields. Health-effect ELVs are used to prevent possible harm from the heating of tissue and electrical stimulation of nerves and tissue caused by exposure to EMFs [28].

Table 6 Action Levels for Electric and Magnetic Field Strength and Magnetic Flux Density RMS values and equivalent power density in the frequency range 100kHz-300GHz [29]

Frequency Range	Electric Field Strength (V/m)	Magnetic Strength (A/m)	Magnetic Flux Density(µT)	Equalent Power Density(W/m^2)
0.1-0.15MHz	87	5	6.25	-
0.15-1MHz	87	0.73/f	0.92/f	-
1-10MHz	$87/f^{1/2}$	0.73/f	0.92/f	-
10-400MHz	28	0.073	0.092	2
400-2000MHz	$1.38f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	f/200
2-300GHz	61	0.16	0.20	10

As per the above table, the restriction values are provided for the electric field strength, magnetic strength, magnetic flux density, and equivalent power density for the frequency range 0.1MHz to 300GHz. For the frequency range 0.1MHz to 10MHz, the action level values are given for the electric field strength, magnetic strength, and magnetic flux density. But from the frequency 10MHz to 300GHz, action level values are given for the equivalent power density with other restriction values.

Table 7 Exposure limit values as the function of the power density of an electromagnetic field in the frequency range 6-300GHz [29]

Frequency Range	Power Density(W/m^2)
6-300GHz	10

According to the above table for the frequency range 6-300GHz (5G frequency range), the exposure limit value is given as the function of the power density of an electromagnetic field.

3.3.2. United Kingdom EMF Regulations

In the UK, OFCOM has issued the regulation guideline [30] for the general public. As per their guideline, they refer to ICNIRP, 1998 and 2020 guidelines and other subsequent versions of the ICNIRP guideline. So, for the general public, the limit values are the same as the ICNIRP guidelines in the UK.

The Health and Safety Executive (HSE) is responsible for ensuring that employees are protected from hazards to their health and safety that may emerge from exposure to electromagnetic fields, or that are likely to arise from such exposure [31]. They published the regulation in 2016 to reduce EMF exposure and those exposure limit values are based on the occupational exposure limits in the INCIRP guideline. Also, Public Health England (PHE) is in charge of public health issues, including those related to electromagnetic fields (EMFs) and they have a statutory obligation to advise the government on the health effects of electromagnetic fields. PHE believes that exposure to radio waves should be to the International Commission on Nonionizing Radiation Protection Guidelines (ICNIRP).

When considering the regulation which was issued by the HSE, it provides on identifying sources of electromagnetic fields (EMFs) in the workplace, assessing the exposure of employees to EMFs, Action Levels (ALs), and Exposure Limit Values (ELVs), deciding what, if anything, needs to be done to protect employees from the risk arising from exposure to EMFs, assessing and controlling any risks from EMFs in the workplace, and protecting employees at specific locations [32].

In HSE regulation, the exposure limit values are mentioned according to the Action Level (AL) and Exposure Limit Value(ELV). These ALs and ELVs are set to account according to their potential effects which are thermal effects and non-thermal effects. Thermal effects are associated with the heating of tissue as a result of the absorption of electromagnetic fields by the tissue. Non-thermal effects caused by the stimulation of nerves or sensory organs in the presence of electromagnetic fields are referred to as non-thermal effects [32].

Table 8 ALs (thermal effects) for exposure to electromagnetic field in the frequency range 100kHz-300GHz [33]

Frequency Range	External Electric field strength ALs (Vm^{-1})	Magnetic flux density Als(B)(μT)	Power density AL (S)(Wm^{-1})
100kHz≤f<1MHz	$6.1x10^2$	$2x10^6/f$	-
1≤f<10MHz	$6.1x10^8/f$	$2x10^6/f$	-
10≤f<400MHz	61	0.2	-
400MHz≤f<2GHz	$3x10^{-3}f^{1/2}$	$1x10^{-5}f^{1/2}$	-
2≤f<6GHz	$1.4x10^2$	$4.5x10^{-1}$	-
6≤f≤300GHz	$1.4x10^2$	$4.5x10^{-1}$	50

According to the above table from frequency 100kHz to 2GHz, exposure limit values are provided for the external electric field strength and magnetic flux density. But for the frequency range 6GHz to 300GHz exposure limit value provides for the power density with values of the external electric field and magnetic flux density.

3.3.3. United States EMF Regulations

In United State Federal Communication Commission (FCC) issued regulations for human exposure to radiofrequency electromagnetic fields in 2013. The Federal Communications Commission's standards distinguish between portable and mobile devices based on their proximity to potentially exposed persons. Specific absorption rate (SAR) restrictions must be used in the evaluation of radiofrequency (RF) emissions from portable devices. RF emissions from mobile devices can be evaluated in terms of Maximum Permissible Exposure (MPE) limits for field strength or power density, or terms of SAR limitations, depending on which method is most appropriate for the particular situation [34].

RF exposure evaluation is performed on mobile devices, which are defined as transmitting devices designed to be used in places other than fixed locations and to be used in a manner in which a separation distance of at least 20 centimeters is normally maintained between the transmitter's radiating structures and the body of the user or nearby persons. when considering the example of mobile devices, cellular and PCS telephones, other radio devices that use vehicle-mounted antennas, and some other transmitting devices.

An RF exposure evaluation definition for a portable device is a transmitting device that is intended to be operated with any part of its radiating structure in direct contact with the user's body or within 20 centimeters of the body of a user or bystanders during normal operating conditions. Hand-held cellular and PCS cellphones that incorporate the radiating antenna into the handpiece, as well as wireless transmitters that are carried close to the body, would fall under this category. The SAR limits for RF exposure are taken into consideration while evaluating portable devices. In the case of portable transmitters used by consumers, the applicable SAR limit is 1.6 watts/kg, which is averaged across any one gram of tissue described as a cube-shaped tissue volume [34].

The regulation values were given according to the occupational/controlled exposure and general population/uncontrolled exposure. Overall, occupational/controlled exposure limits apply in cases when individuals are exposed as a result of their work, who have been made fully aware of the possibility of exposure, and who can exert control over their exposure. It is also applicable when the exposure is transient as a result of incidental passage through a location where the exposure levels may be higher than the general population/uncontrolled limits, but the exposed person is fully aware of the potential for exposure and can exercise control over his or her exposure by leaving the area or employing some other appropriate method [34].

Generally, the general population/uncontrolled exposure limits apply to situations in which the general public may be exposed, or in which individuals who are exposed as a result of their employment may not be made fully aware of the potential for exposure or may not be able to exert control over their exposure [34].

Table 9 Exposure limit values for Occupational/Controlled Exposure [34]

Frequency Range (MHz)	Electric Field Strength(V/m)	Magnetic Field Strength (A/m)	Power density (mW/cm^2)	Averaging time(minutes)
0.3-3	614	1.63	100^*	6
3-30	1842/f	4.89/f	$900/f^{2*}$	6
30-300	61.4	0.163	1	6
300-1500	-	-	f/300	6
1500-100000	-	-	5	6

Table 10 Exposure limit values for General Population/Uncontrolled Exposure [34]

Frequency Range (MHz)	Electric Field Strength(V/m)	Magnetic Field Strength (A/m)	Power density (mW/cm^2)	Averaging time(minutes)
0.3-1.34	614	1.63	100^*	30
1.34-30	824/f	2.19/f	$180/f^{2*}$	30
30-300	27.5	0.073	0.2	30
300-1500	-	-	f/1500	30
1500-100,000	-	-	1.0	30

f=frequency in MHz *= Plane -wave equivalent power density

Table 9 and Table 10 show the exposure limit values for the occupational and general population. According to the above table from the frequency 0.3MHz to 300MHz, the exposure values are given by the terms of electric field strength, magnetic field strength, and power density. But from the frequency 300MHz to 100,000MHz the exposure values are given in terms of power density.

3.3.4. South Korea EMF Regulations

Korea's policy on electromagnetic fields and radiofrequency usage is governed by the Radio Waves Act. It specifies that all radio facilities must be installed and changed in compliance with safety recommendations to ensure the public's safety and protection against electromagnetic field exposure. The MSIT is responsible for establishing limits on EMF emissions to safeguard the human body, as well as for overseeing the method of measuring SAR, the electromagnetic fields released, and the devices employed.

The RRA announces each measurement standard for electromagnetic field intensity and SAR by the applicable regulations. The devices and installations that are subject to SAR and electromagnetic field strength regulations are outlined in detail in a separate notification. The results of the assessment of the electromagnetic field level for broadcasting stations and base stations (aggregated antenna power greater than 30 W or 60 W, depending on the type of communication system) must be reported before putting into service or during the periodic inspection of the communication system, respectively (5-year terms). In the Republic of Korea, they adopt the ICNIRP 1998 reference levels. Also, they are following the SAR levels as per the guidelines followed by the USA and Canada.

4. REGULATIONS FOR ELECTROMAGNETIC FIELD IN 5G AND LITERATURE REVIEW

This chapter discussed the regulations for electromagnetic fields in 5G and compare the regulations by considering the countries. And also, this chapter will discuss the existing research done in EMF in 5G.

4.1. Regulations for EMF in 5G

Most RF exposure limits in the world are based on the limits which are developed by the International Commission on Non-Ionizing (ICNIRP) or the International Committee on Electromagnetic Safety which develops the IEEE standards. These limits are defined in terms of specific absorption rate (SAR), electric and magnetic field strength, and power density in the 5G frequency band. The exposure limits are different in some countries and restrictive. International Telecommunication Union (ITU) recommends that if radiofrequency electromagnetic field (RF-EMF) limits do not exist, or if they do not cover the frequencies of interest, then ICNIRP limits should be used. ICNIRP continuously monitors the effect of the EMF through scientific research to ensure up-to-date human exposure guidelines.

The Council of the European Union has provided exposure to general-public reference levels by considering the frequency ranges. By the ICNIRP recommendations, these recommendations are referred over six minutes. These reference levels are determined by the RMS(Root-Mean-Square) value of the electric field strength E and the equivalent plane wave power density *S*.

Many countries are accepted the ICNIRP guidelines including most EU countries. But some countries have their legal regulations to protect the people and environment from EMF exposure. Austria, Denmark, Latvia, Netherland, Sweden, and the UK has milder restrictions to protect people from EMF exposure compared to ICNIRP. Belgium, Bulgaria, Croatia, France, Greece, Italy, Lithuania, Luxembourg, and Poland have more restriction national-level regulations [34]. The government of the Brussels Capital Region has approved an increase in local radio frequency emissions, making it possible for 5G services to go ahead in the Belgian capital. The maximum limit will increase to 14.5 volts per meter, from the current 6 V/m. This covers mobile networks, as well as radio and TV antennas [36].

The three primary frequency bands for 5G standards that have been adopted globally are low band, mid-band, and high band. Under mid-band, 1GHz frequencies are used, and typically 600/700MHz in the European Union, the United States of America, and India. In the EU, Korea, China, and India, the mid-band range (3-5GHz) is used, while the USA uses the 2GHz frequency. When it comes to the high band (20-100 GHz), the EU, Korea, and the USA all use it [37].

The power density reference levels are regulated in a similar manner in the United States and Japan. The power density restrictions in Japan are the same as those in the FCC's guidelines. In Japan, the radio frequency limit is 300GHz. However, in the United States, the top frequency limit is 100GHz [35]. In USA and Japan, when considering the frequency range 1500-100,000MHz limit values for the general population/uncontrolled exposure are provided for the electric field (61.4V/m) and power density (1mW/cm^2) [38].

4.2. Comparison of EMF regulations

The following table shows the comparison of the global, regional, and country-specific regulations with the parameters of incident electric field strength, incident magnetic field strength, and incident power strength. According to the regulations, two frequency ranges were used to compare the values.

Table 11 Comparison of Reference Levels for General Public in 5G frequency range

	ICNIRP		European council		Finland		USA	UK	
	400-2000MHz	2-300GHz	400-2000MHz	2-300GHz	400-2000MHz	2-300GHz	1.5-100GHz	400-2000MHz	2-300GHz
Incident E-field Strength (Vm^{-1})	$1.375f_M^{0.5}$	-	$1.375f_M^{0.5}$	61	$1.38f_M^{0.5}$	61	-	$1.375f_M^{0.5}$	-
Incident H-field strength (Am^{-1})	$0.0037f_M^{0.5}$	-	$0.0037f_M^{0.5}$	0.16	$0.0037f_M^{0.5}$	0.16	-	$0.0037f_M^{0.5}$	-
Incident Power Strength (Wm^{-2})	$f_M/200$	10	$f_M/200$	10	$f_M/200$	10	10	$f_M/200$	10

When considering the ICNIRP, European Council, and Finland the limit values for the incident E-field, H-field, and power density at the frequency range 400-2000MHz are the same. However, there were no limit values for incident E-field strength and incident H-field strength in the ICNIRP guideline for the frequency range 2-300GHz. The European Council, on the other hand, specifies $61Vm^{-1}$ for incident E-field strength and 0.16 Am^{-1} for incident H-field strength. Finland used the same values for these parameters as the European Council. However, the incident power strength values of the ICNIRP, the European Council, and Finland are all the same ($10W/m^{-2}$).

Only the limit values up to 100GHz were published in the United States. So, the frequency range 1.5-100GHz, and there were no limit values for the incident E-field strength and incident H-field strength. However, there is an incident power strength value, which is equal to the ICNIRP, European Council, and Finland incident power strength values. For the general public, the UK also refers to the ICNIRP guideline, and the limit values are the same.

When considering the exposure limits of the general public in Europe Union countries such as the Czech Republic, Estonia, France, Greece, Hungary, Ireland, Luxembourg, Portugal, and Romania [39], the EU's recommendation has been implemented into national law or policy. The reference levels in the Czech Republic differ from those recommended by the European Union, but the basic restrictions are the same. In Germany and Slovakia, the reference levels of the Europe Union recommendation are applied as de facto exposure limits [39] without reference to basic restrictions.

In France, as per the national recommendations when the design of new hospitals, maternity wards, and children's facilities are near power lines, cables, transformers, and bus bars, they should prevent it as far as possible [39]. Also, when planning a new grid development, the grid operator should avoid infrastructure near these locations. In German, they recommend that for newly planned buildings the high voltage power lines for AC may not pass over the building. The locations with homes, hospitals, schools, childcare facilities, playgrounds, or any other location where people are temporary stay for a short time must keep electromagnetic fields (EMF) as low as possible.

Building permanent residences should be avoided in Finland, according to the Radiation Safety Authority (STUK) if the magnetic flux density continuously exceeds the level of 0.4 microtesla [38]. In Nederland also there is a national recommendation to prevent creating new situations with a long-term stay of children in areas [39] overhead high voltage power lines with annual averaged magnetic flux density greater than 0.4 microtesla.

When considering the limitations of the guidelines, the USA and Japan consider the same power density levels [38]. For 5G frequency range 2-300GHz it is 10W/m^2. But in the USA the upper-frequency range is 100GHz not 300GHz as in Japan and the ICNIRP guideline. The Republic of Korea accepts the ICNIRP 1998 reference levels [35] also Korea follows the SAR levels of Canada and the USA. For below 2GHz frequencies Switzerland and Italy apply up to 0.01 reference level for power density as per the ICNIRP 1998 guideline. Also, in Switzerland as a fundamental limitation on total exposure [38] they use the ICNIRP and then add the Installation Limit Values layer. For sensitive places such as apartment buildings, schools, hospitals, permanent workplaces and children's playgrounds Switzerland implements the safety exposure limits.

For the frequency range 300MHz-300GHz, Polish exposure limits for the general public is 0.1W/m^2. As per the ICNIRP guideline, this value is 10W/m^2. This means polish exposure limits are 100 times more restrictive. For exposure limits, the past Polish used two zones that are temporary presence and permanent presence. For temporary presence, the limit was 0.1W/m^2 and for permanent presence, it was 0.025W/m^2. At present, they used only one limitation (0.1W/m^2). Hungary also used ICNIRP exposure limitations. Also, Luxembourg made national exposure limits by reducing the ICNIRP limitations by 20 times [38].

4.3. 5G Network Planning with EMF

This section summarizes existing research on 5G network planning under EMF constraints. It is important to consider the EMF exposure from the transmitter antenna to the human when planning the network. The following subsection examined available approaches for assessing EMF exposure during network planning.

4.3.1. Power Density Assessment

When planning the network or introducing the mm-Wave band device to the market [39], it is critical to adhere to the various exposure limits specified in numerous standards and specifications. The specific absorption rate (SAR) has frequently been employed as a tool for determining compliance with exposure limits. This is the metric used to determine how much energy is absorbed by the human body while using a mobile phone. However, because this absorption is limited to the skin at high frequencies, it is extremely difficult to use the SAR as a measure of the exposure limit. As a result, the power density (PD) of the 5G network is measured in W/m2.

When it comes to limiting exposure to electromagnetic fields, the International Commission on Non-Ionizing Radiation Protection's (ICNIRP) 2020 guidelines for limiting exposure to electromagnetic fields specify a general public exposure limit of 10 Wm^2 [3] for frequencies between 2 and 300 GHz, with an averaging time of 30 minutes. Similar limits are specified by the European Council, the Finnish Radiation and Nuclear Safety Authority(STUK), and Federal Communication Commission.

To analyze the exposure, power density(P_D) radiated by a transmit antenna can be expressed as follows.

$$P_D = \frac{G_T P_T}{4\pi d^2} \quad (2)$$

Here G_T is transmitting antenna gain in dBi, P_T is transmitting antenna power in dBm and d is the far-field distance. Far-field distance is defined as Fraunhofer distance and it can be expressed as follows.

$$d_{far\_field} = \frac{2D^2}{\lambda} \quad (3)$$

Where D is the largest dimension of the antenna and λ is the wavelength that corresponds to a frequency of operation [40]. It would be necessary to resort to numerical modeling approaches such as the finite element method or finite-difference time-domain at distances shorter than the far-field distance to compute the power density at such short distances. Because when the distance is less than the far_field distance, the power density cannot compute by using the equation(2).

According to the simulation performed in (2), power density decreases as distance increases. This simulation was conducted in a specific location of Austin, Texas for various transmitting power and gain settings, and all of the values are less than the maximum power density of 10W/m2.

Another simulation was carried out within the Cumulative Distribution Function(CDF) and the power density for both pre-existing LTE networks and the deployed 5G network. As per the results, the potential radiation levels that will be reached upon the rollout of 5G networks do not meet any of the exposure limitations that have been established. According to the results they suggested that 5G mobile networks are not yet considered to be safe for the general public and that considerable thought should be made before implementing mmWave communications for 5G networks due to the possible harm it could cause to the general public [40].

4.3.2. Synthetic Model and Ray Tracing Algorithms

Ray tracing methods make use of a straightforward approach that employs antenna pattern synthesis and spherical free-space wave propagation to determine approximate field values in both the near-field and far-field antennas that are radiating in the same direction. The spatial peak and spatially averaged RF field strength can be calculated by utilizing the far-field spherical equations [41]. The spatially averaged and spatial-peak equivalent power densities can be evaluated as follows.

$$S = \frac{\bar{P}_{avg}.G_{\theta,\varphi}}{4.\pi.r^2} \quad (4)$$

If the reflecting ground plane is present, the following equation can be used.

$$S = (1 + |\Gamma|)^2.\frac{\bar{P}_{avg}.G_{\theta,\varphi}}{4.\pi.r^2} \quad (5)$$

For a theoretical highest field strength scenario of a perfectly conducting ground plane $|\Gamma|=1$ or for typical ground reflection condition $|\Gamma|=0.6$ [42].

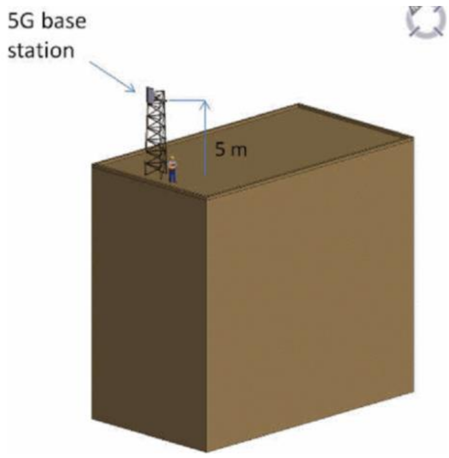

Figure 6 Assessed 5G macro site with a 3.5GHz massive MIMO base station. [41]

When calculating the power reduction factor for this assignment, it is taken into consideration that the power or EIRP is spreading in a different direction during the 6-minute average period. According to IEC TR 62669, statistical methods were used to establish the cumulative distribution function (CDF) of the power reduction factor for an 8x8 mMIMO antenna in both rural and urban installation scenarios situations. In this study, a power reduction factor of 0.32 was chosen [40], and simulation was carried out with the actual maximum power of 50W.

After the simulation is carried out with equation (4), the minimum vertical distance between a rooftop and its bottom edge of compliance boundary for members of the general public and employees is lower than the height of the rooftop. That means according to the results if the rooftop is accessible for both the general public and workers [41]. So, the RF-EMF exposure is below the acceptable levels.

5. SIMULATION SYSTEM MODEL

In this section, we will discuss how the 5G environment was set up and how we measure EMF exposure in terms of power density for the general public in our system model. Two methods were used to assess EMF exposure in this study. First, the minimum safe distance between the transmitter and the general public was calculated. As a second method, power density was calculated and the effect of increasing distance on power density was examined.

5.1. 5G Environment Setup

To set up the 5G environment, cell radius was calculated by considering the path loss model and the link budget estimation. The free space reference distance (CI) path loss model was considered as a path loss model [43] for this research. The path loss model was considered for the different environment scenarios such as Urban Macrocell Line of Sight (Uma LOS), Urban Macrocell(Uma NLOS), Urban Microcell Street Canyon Line of Sight(UMi-S.C LOS), Urban Microcell Street Canyon Non Line of Sight(UMi-S.C NLOS), Urban Micro Open Square Line of Sight(Umi-O.S LOS), Urban Micro Open Square Non-Line of Sight(Umi-O.S NLOS).

$$PL^{CI}(f,d)[dB] = FSPL(f,1m) + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}^{CI} \quad (6)$$

Where f is the operating frequency in *Hz* and *d* is the distance between the transmitter and the mobile station in meters. Free space path loss(FSPL) for a frequency of *f* is given by,

$$FSPL(f,1m) = 20log_{10}\left(\frac{4\pi f}{c}\right) \quad (7)$$

Then CI path loss model can be rewritten as,

$$PL^{CI}(f,d)[dB] = 20log_{10}\left(\frac{4\pi f}{c}\right) + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}^{CI} \quad (8)$$

X_{σ}^{CI} is the shadow fading (SF) in terms of dB. It is a zero-mean Gaussian random variable with a standard deviation σ in dB. The standard deviation of this random variable is,

$$\sigma^{CI} = \sqrt{\sum X_{\sigma}^{CI^2}/N} = \sqrt{(PL^{CI} - FSPL - n10log_{10}(d))/N} \quad (9)$$

CI model parameters are different from one scenario to another and the following table shows how those values are changing according to the scenarios.

Table 12 CI Parameter values for different environment scenarios of CI path loss model [43]

Scenario	CI Model Parameters
UMa-LOS	n=2.0, SF=4.1dB
UMa-NLOS	n=3.0, SF=6.8dB
UMi-S.C-LOS	n=1.98, SF=3.1dB
UMi-S.C-NLOS	n=3.19, SF=8.2dB
UMi-O.S-LOS	n=1.85, SF=4.2dB
UMi-O.S-NLOS	n=2.89, SF=7.1dB

The link budget of the 5G NR connection, can be calculated as follows. Here assume that the attenuation due to rain and fog is equal to the 0.

$$P_{Rx}[dBm] = EIRP[dBm] - PL^{CI} + G_{Rx} \quad (10)$$

P_{Rx} is the power received by the mobile station(the signal level at the receiver). G_{Rx} is the antenna gain in dBi of the mobile station and the effective isotropic radiation power (EIRP) can be calculated by:

$$EIRP[dBm] = P_{Tx} + G_{Tx} - L_{Tx} \quad (11)$$

Once we know the path loss, then it is possible to calculate the cell radius with the use of receiver sensitivity.

$$Receiver\ Sensitivity(dBm) = Noise\ Figure(dB) + Thermal\ Noise(dBm) + SINR(dB) \quad (12)$$

To calculate the path loss, the link budget formula (11) can be used and the signal level at receiver P_{Rx} can be replaced with the receiver sensitivity.

$$PL^{CI} = EIRP(dBm) + G_{Rx\_}Receiver\ Sensitivity(dBm) \quad (13)$$

Following the calculation of the path loss value, the cell radius can be calculated using formula (8) and table 12. Table 13 shows the simulation parameter values which was used to calculate the cell radius.

Table 13 Link budget-specific simulation parameter values [44]

Parameter	Value
Frequency (f)	3.5GHz
Max EIRP	41dBm
Antenna Gain (G_{Tx})	6dBi
Transmission Power (P_{Tx})	35dBm
Receiver Antenna Gain (G_{Rx})	0 dBi
Receiver Sensitivity	-78
BS Antenna Hight	6m

By using the link budget equation in (12) and considering the simulation parameters given in table 13, the cell radius can be calculated for different scenarios. The required number of base stations for the selected area is determined after calculating the cell radius. The following equation can be used to calculate the coverage of a single base station over a square area.

$$Coverage\ area = R^2\pi \tag{14}$$

After calculating the coverage area, the required number of 5G base stations can be determined as follows.

$$No.of\ 5G\ gNodeB = \frac{S_q}{C_a} \tag{15}$$

where S_q is the total surface area of the cluster in a square area and C_a is a single gNB's coverage area.

5.2. Minimum Safety Distance Calculation

In this section, we present how to calculate the minimum distance between the mobile user and the transmission antenna. The INCIRP general public limitation for the 5G network, which was 10W/m2 in a term of power density was used for this simulation. For this calculation as an input parameter, transmitter power (EIRP) in Watts and operating frequency was used. The power density can be found by using the following formula:

$$S = (1 + |\Gamma|)^2 \frac{P_t}{4\pi R^2} \tag{16}$$

The minimum distance (R) between the transmitter and the general public can be calculated as,

$$R = \sqrt{\frac{P_t(1+|\Gamma|)^2}{4\pi S}} \tag{17}$$

where S is the power density in W/m^2, P_t is transmitter power which is specified in EIRP in Watts, R is the radius in meters which is measured from the center of the antenna and $|\Gamma|$ is the reflection coefficient. Here is a reflection coefficient ($|\Gamma|$) =0.6. Here we assumed that the minimum distance between the transmitter and the general public is never shorter than the reactive near the field boundary of the antenna. Reactive near field boundary is calculated as ($\lambda/2\pi$) where λ is the wavelength in meters.

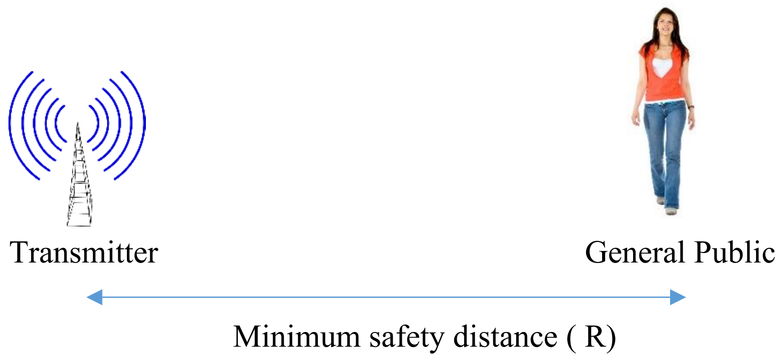

Figure 7 Minimum distance between the transmitter and the general public

The simulation parameters listed below were used to determine the minimum safe distance between the transmitter and the general public. This research always used worst-case values for the simulation. Therefore, with worse-case values, the maximum safety distance is calculated. So, for the simulation, maximum antenna gain and maximum power of the transmitter were used. Also, free space propagation is usually taken between the transmitter and the general public even though there are obstacles between the antenna and the general public. Here maximum transmission time of thirty minutes is used for this calculation. because in the 2020 ICNIRP guideline the averaging period is defined as thirty minutes.

Table 14 Simulation parameters for minimum distance calculation [45]

Parameter	Value
Frequency (f)	3.5GHz
Maximum Transmission time	6 minutes
Power density	10W/m^2
Reflection Coefficient (Γ)	0.6

5.3. Power Density Assessment

To analyze the radiation in the 5G network we used power density assessment. The ICNIRP recommendation, Europe Council, Finland, and the United States all use the same power density value (10W/m^2) for frequencies ranging from 2 to 300GHz for the general public.

The power density was calculated using the equation below. By that EMF exposure can be analyzed with the exposure limit value.

$$S = \frac{P_T * G_T}{4\pi R^2} \quad (18)$$

Where P_T is the power of the transmitting antenna, G_T is the gain of the transmitting antenna and R is the distance between the antenna and the general public. The antenna's power is measured in dBm, and its gain is measured in dBi. So, before putting the equation together, the power value must be converted into Watts and the gain value into the linear. As a result, the following equations were used to convert power and gain values into Watt and linear values:

$$P(Watt) = \frac{10^{\frac{P(dBm)}{10}}}{1000} \quad (19)$$

$$G_T = 10^{\frac{G_T(dBi)}{10}} \quad (20)$$

According to above (18)-(20) power density was calculated by one transmitter and analyzed the performance of power density when increasing the distance in three different frequency bands 700MHz, 1800MHz, and 3.5GHz. Here the distance between the transmitter and the general public is taken 198m which was the cell radius for the Uma-NLOS scenario.

Table 15 Simulation parameters for power density assessment in three frequency bands [44][46][47]

	700MHz	1800MHz	3.5GHz
Transmitter Power (P_T)	23dBm	23dBm	35dBm
Transmitter Gain (G_T)	15dBi	4dBi	6dBi
Transmitter antenna height (h_t)	30m	3m	6m
Receiver Antenna height (h_r)	1.5m	1.5m	1.5m

Then the simulation was carried out for the different environmental scenarios and analyzed the performance of power density when increasing the distance. This analysis took into account the following test environments.

- **Indoor hotspot-eMBB:** This type of indoor isolated environment is found in offices and/or shopping malls. This is consisting of one floor of a building with a height of 3m. the floor has a surface area of 120m x 50m and 12BSs/sites which are placed in 20m spacing [48]
- **Dense Urban-eMBB:** An urban environment with high user density and traffic loads focusing on pedestrian and vehicular users [48]. This environment consists of two layers which are the macro layer and microlayer. The macro-layer base stations are placed in a regular grid, following a hexagonal layout with three TRxPs each, and in the microlayer, there are 3 micro sites randomly dropped in each macro TRxP area [48].
- **Rural-eMBB:** A rural environment with larger and continuous wide area coverage, supporting pedestrian, vehicular, and high-speed vehicular users [48]. In this environment, Base stations/sites are placed in a regular grid which is following the hexagonal layout with three cells each.
- **Urban macro mMTC:** It targets continuous coverage based on a large number of connected machine-type devices [48].
- **Urban Micro URLLC:** It targets ultra-reliable and low latency communication.

Table 16 Simulation parameters for different environmental scenarios [48]

	Indoor hotspot	Dense Urban	Rural	Urban macro mMTC	Urban Micro URLLC
Operating Frequency (Hz)	4GHz	4GHz	700MHz	700MHz	4GHz
Transmitter Power (P_T)	24dBm	44dBm	49dBm	49dBm	49dBm
Transmitter Gain (G_T)	5dBi	8dBi	8dBi	8dBi	8dBi
Transmitter antenna height (h_t)	3m	25m	35m	25m	25m
Receiver Antenna height (h_r)	1.5m	1.5m	1.5m	1.5m	1.5m

To analyze the EMF exposure power density assessment for the typical 5G network following simulation parameters were used. The parameter value here is not for a single antenna. The transmitter power in the indoor hotspot at the frequency 3.5GHz, dense urban, micro, and micro RRH is for four transmitters. However, the transmitter power in the 26GHz hotspot scenario is for two transmitters.

Table 17 Simulation parameters for typical 5G network power density assessment

	Indoor hotspot	Indoor hotspot	Dense Urban	Micro	Micro RRH
Operating Frequency (Hz)	3.5GHz	26GHz	3.5GHz	4200MHz	4200MHz
Transmitter Power (P_T)	30dBm(for 4Tx)	35.05dBm(for 2 Tx)	46.02dBm(for 4 Tx)	39.0dBm(for 4 Tx)	49.03dBm(for 4Tx)
Transmitter Gain (G_T)	0 dBi	23 dBi	10dBi	17dBi	18dBi
Transmitter antenna height (h_t)	3m		5-10m	25m	25m
Receiver Antenna height (h_r)	1.5m	1.5m	1.5m	1.5m	1.5m

The three transmitters in the 700MHz, 1800MHz, and 3.5GHz frequency bands were then co-located. We aim at figuring out how much EMF exposure there would be if multiple network providers co-located their transmitters on the same site when deploying the 5G network. This simulation used the same simulation parameters as in table 15. When the general public moves far away from the transmitter, the power density performance was examined.

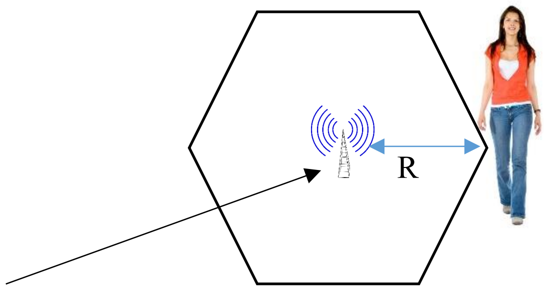

Figure 8 The general public is in cell radius (R) distance from the co-located transmitter

5.4. Calculating Aggregate Power

Under this section, aggregate power was calculated to analyze the EMF exposure from the one transmitter antenna. As per the deployed 5G network with a 3.5GHz frequency band, by using equation (15) we calculated the number of the transmitters in the planning network. But for this calculation, we considered three cells and assumed that the general public is in the cell radius (R) distance from each cell as per figure 9. Then the aggregate power was calculated and analyzed the EMF exposure of the person.

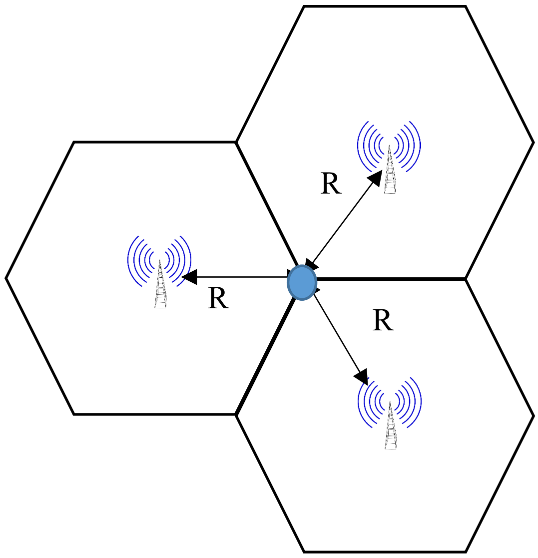

Figure 9 Aggregate power calculation when the general public is in cell radius distance

As a second step aggregate power was calculated by using equation (18) to analyze the EMF exposure from the co-located transmitter. The transmitters with frequency bands of 700MHz, 1800MHz, and 3.5GHz were co-located for this analysis.

6. RESULTS

This chapter comprises the result of the simulations and the analysis of the results. The simulation results consist of cell radius for different scenarios, power density assessment for different frequencies, different environment scenarios, typical 5G network, and co-located transmitter.

6.1. Cell Radius for different scenarios

By using the link budget equation in (13) and the simulation parameters given in table 13, the following cell radius was calculated by using MATLAB according to different scenarios. For this research, all the calculations will do by using the cell radius of 198m for the Uma-NLOS scenario.

Table 18 Cell radius for different scenarios

Scenario	Cell radius (m)
UMa-LOS	3.79×10^3
UMa-NLOS	197.64
UMi-S.C-LOS	4.63×10^3
UMi-S.C-NLOS	130.39
UMi-O.S-LOS	7.3×10^3
UMi-O.S-NLOS	236

6.2. Number of base stations

By using the equation (14) coverage area by the one transmitter was calculated by considering the Uma-NLOS scenario. According to the scenario, the cell radius is 198m and the coverage area by one transmitter is **0.123km^2**. If we assume that we are planning a 5G network for the 1km x 1km square area, by using the equation (15) number of required transmitters can be calculated. So as per the calculation number of transmitter antennas to cover the 1km^2 is **8**. Micro base station simulation parameters in the table (13) were used for the above calculation with a 3.5GHz frequency, and the base station antenna height is 6m. As a result, this base station antenna covers 0.123km^2, whereas a 1 km^2 square area requires 8 antennas operating at 3.5GHz.

6.3. Minimum Safety Distance

When there is a single transmitter with an operating frequency 3.5GHz and the transmitter is transmitting the 6 minutes in any 30 minutes, by using equations (15) and (16) the minimum distance between the transmitter and the general public is 0.8m. Here 30 minutes time interval was selected because in the ICNIRP guideline reference level for EMF exposure from 100kHz to 300GHz were taken for an average of over 30 minutes.

A 3.5GHz microcell base station was used to calculate the minimum safe distance. As this assessment is for general public EMF exposure, the power density is set to 10W/m^2 per the ICNIRP guidelines. This evaluation is limited to a single transmitter. So, based on the simulation results, we can conclude that if a person is above 0.8m, she or he is safe from EMF exposure from the transmitting antenna. So, for the Uma-NLOS scenario, this transmitter covers a 0.123km^2 area. As a result, when compared to the coverage area, this distance is very short.

6.4. Power Density Assessment for Different Frequencies

To analyze the power density in different frequencies, 700MHz, 1800MHz, and 3.5GHz frequency band transmitters were used. The power density was calculated by using equations (18)-(20) and power density performance was analyzed when increasing the distance. An analysis of power density performance was conducted up to 10 meters.

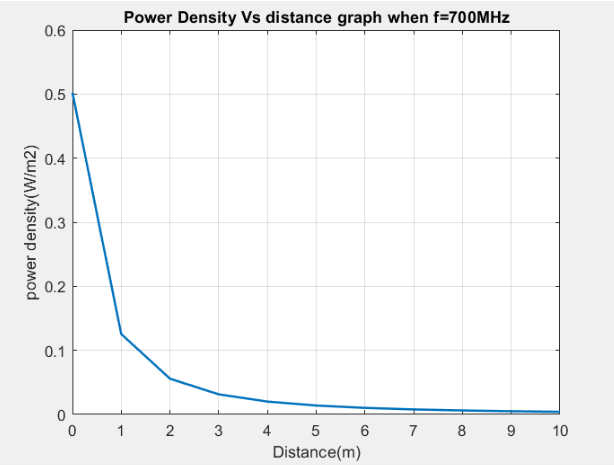

Figure 10 Power density Vs Distance graph when f=700MHz

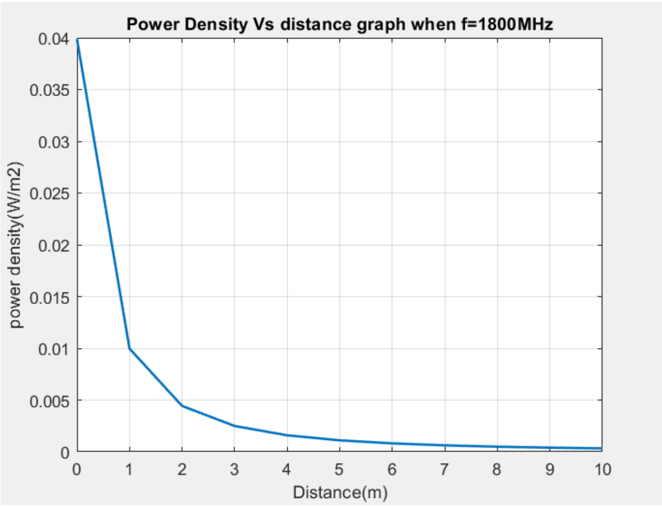

Figure 11 Power density Vs Distance graph when f=1800MHz

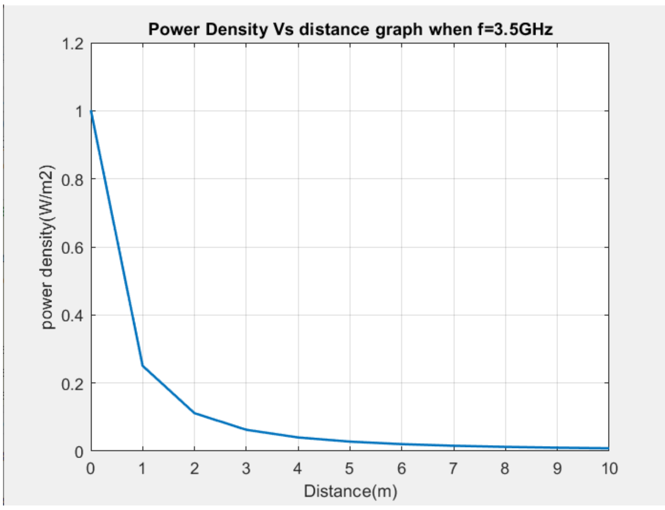

Figure 12 Power density Vs Distance graph when f=3.5GHz

Figures 10,11,12 show the changes in power density with three different frequencies in the distance range of 0 to 10 meters. When considering the 700MHz, at the starting point power density is 0.5W/m^2 and when the distance is increasing power density values are decreasing. As per the ICNIRP guideline, the power density value for the general public should be less than 10W/m^2. At all three frequencies, starting power density value is less than 10W/m^2 and when the distance is increasing power density value is decreasing and it going to zero. 5G network planning was done for the frequency 3.5GHz and according to that frequency corresponding power density at 1 meter is 1W/m^2. These three power density values for 700MHz,1800MHz, and 3.5GHz comply with the limits set by the ICNIRP.

When the person is in the cell radius(R) distance which is 198m, by using the above (18)-(20) equations, the power density is **3x10^{-5}W/m^2**.

The maximum power density, according to the ICNIRP guidelines, should be 10W/m^2. However, when a person is in the cell radius distance of a deployed 5G network, the power density is very low. The power density value decreases as the distance increases. As a result, when the person is within the cell radius distance, the power density is very low.

If the person is at the same distance (R) from each transmitter and the transmitters have the same simulation parameters, the aggregate power of the power can be calculated as:

= 3x10^{-5} *3 = **9x10^{-5} W/m^2**

According to the above power density value, the person's cell radius distance from the three transmitters with the frequency 3.5GHz is very small. That means if the person is far away from the transmitters, there is less EMF exposure. So minimum distance should be calculated from the base station to the general public and above the minimum distance which is 0.8m, we can say that the EMF exposure is low.

6.5. Power Density Assessment for Different Scenarios.

The power density was then calculated for each of the different scenarios, and the results, which show how it changes with distance, are shown in the graphs below. The simulation results show for the indoor hotspot, dense urban, rural, urban macro mMTC, and urban micro URLLC scenarios. The simulation used 4GHz for indoor hotspots, dense urban and urban micro URLLC, and 700MHz for rural and urban macro mMTC. The height of the antenna is the same for the dense urban, urban macro, mMTC, and urban micro URLLC. For the indoor hotspot, it was 3m and for the dense urban area, it was 25m.

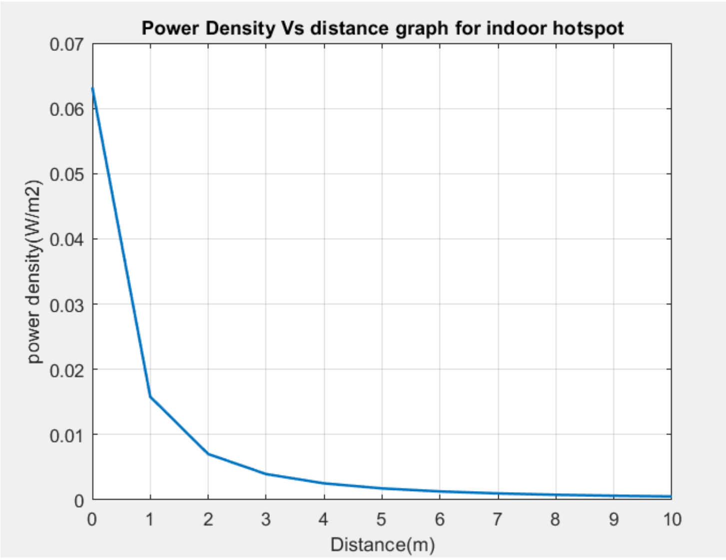

Figure 13 Power density Vs Distance graph for indoor hotspot scenario when f=4GHz

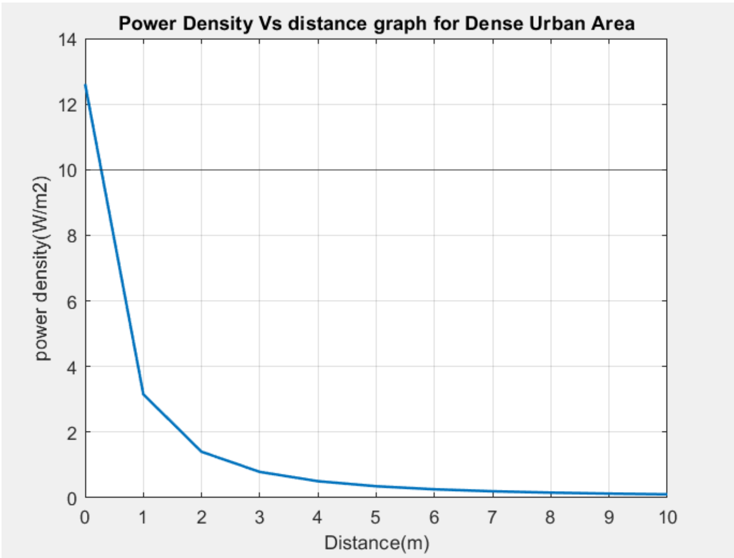

Figure 14 Power density Vs Distance graph for Dense Urban Area when f=4GHz

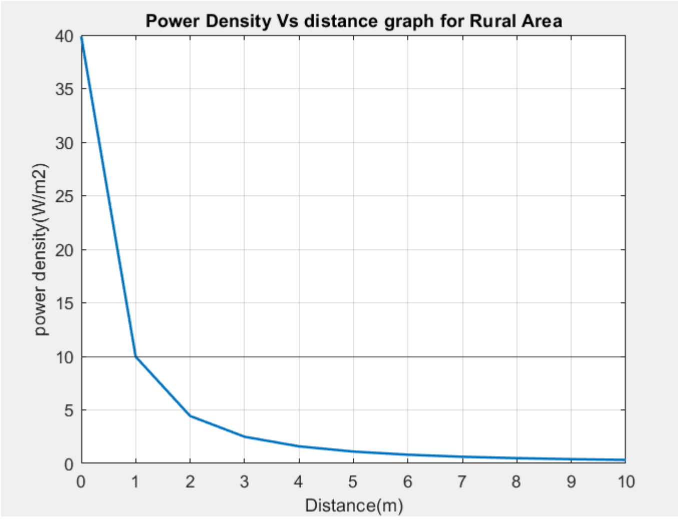

Figure 15 Power density Vs Distance graph for Rural Area when f=700MHz

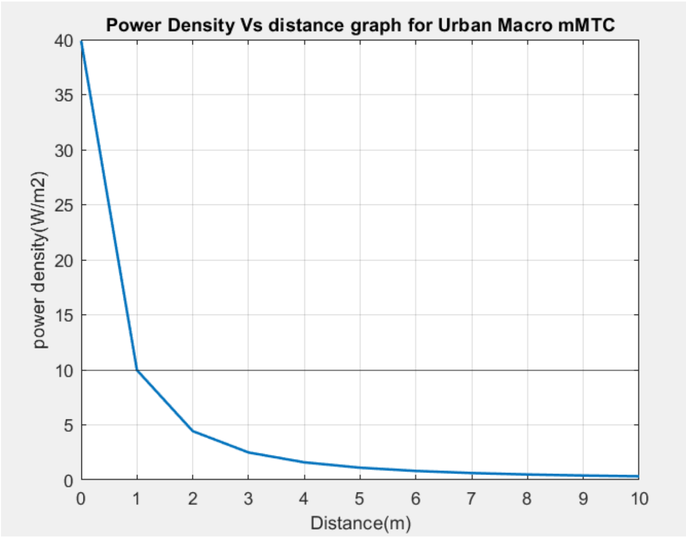

Figure 16 Power density Vs Distance graph for Urban Macro mMTC when f=700MHz

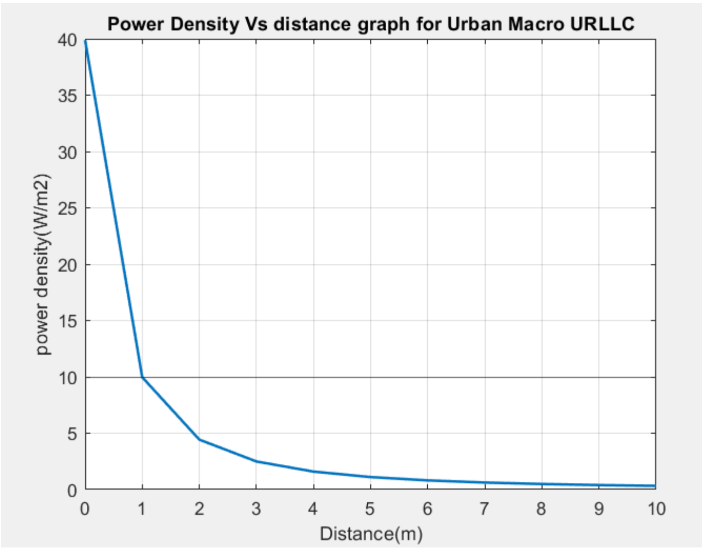

Figure 17 Power density Vs Distance graph For Urban Macro URLLC when f=4GHz

Figure 13 shows the power density changing when increasing the distance. At the beginning power density is $0.063W/m^2$and when the distance is increasing to 10m, the value of power density is decreasing. When considering the graph of the dense urban area(Figure 14), in the beginning, the power density value is $12.61W/m^2$ and when 10m its value is $0.1261W/m^2$. However, until a distance of 0.3m, the power density value is greater than $10W/m^2$, which is the maximum value for the general public according to the ICNIRP guidelines. However, after 0.3m, the power density decreases, indicating that people are no longer exposed. As a result, according to Figure 15, the minimum distance for the general public in a dense urban area is 0.3m.

As per Figure 15, the power density graph starts with the value $40W/m^{2,}$ and until 1m the values are greater than $10W/m^2$. So according to the guidelines vale of the general public, the minimum distance between the transmitter and the general public is 1m for the rural area scenario. When considering the Urban Macro mMTC scenario, the minimum distance is 1m as per Figure 16. That distance is equal to the rural area configuration. When considering the simulation parameters in rural are and the Urban Macro mMTC are the same except for the height of the transmitter antenna height.

According to figure 17, the minimum distance is 1m. The graphs for rural areas, Urban Macro mMTC, and Urban Macro URLLC are all the same. The minimum distance for all scenarios is 1m, and the power density at the starting point is $40W/m^2$. However, the height of the transmitter in rural areas and Urban Macro mMTC configurations is not the same. It is 35m in the rural area and 25m in the Urban Macro mMTC area. When considering the Urban Macro URLLC, the operating frequency is 4GHz, while the other two scenarios are 700MHz.

6.6. Power density assessment for typical 5G network

For this simulation, practical transmitter power and gain were used for the simulation to analyze the EMF exposure of different scenarios. The performance of power density with distance was analyzed for indoor hotspots, dense urban, urban micro, and micro RRH scenarios. For the indoor hotspot 3.5GHz and 26GHz frequency bands are used and analyzed the performance. These transmitter powers are not only for one transmitter. For an indoor hotspot with the frequency 3.5GHz, dense urban, micro, and micro RRH simulation transmitter antenna power is for four transmitters and an indoor hotspot with the frequency 26GHz is for two transmitters.

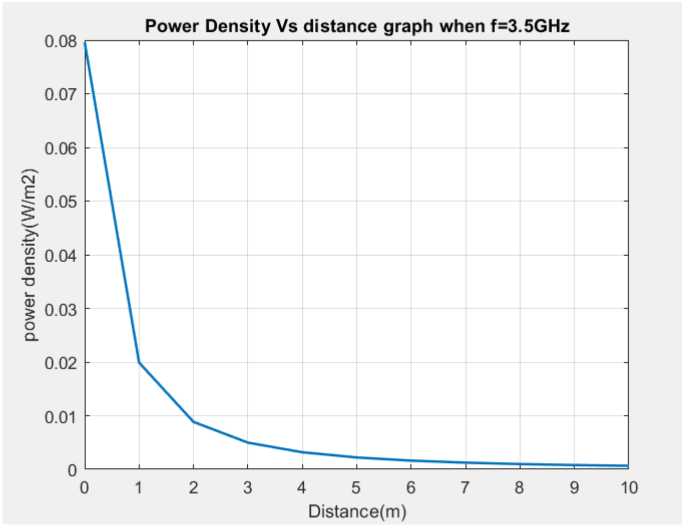

Figure 18 Power density Vs Distance Graph for Typical Indoor Hotspot When f=3.5GHz

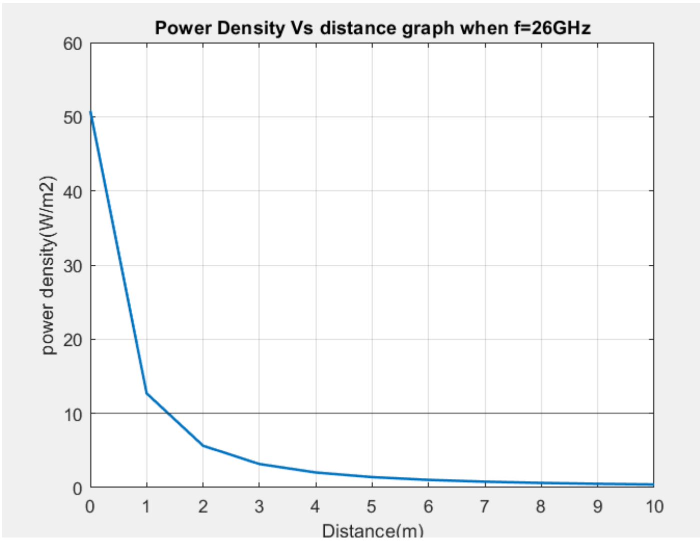

Figure 19 Power density Vs Distance Graph for Typical Indoor Hotspot When f=26GHz

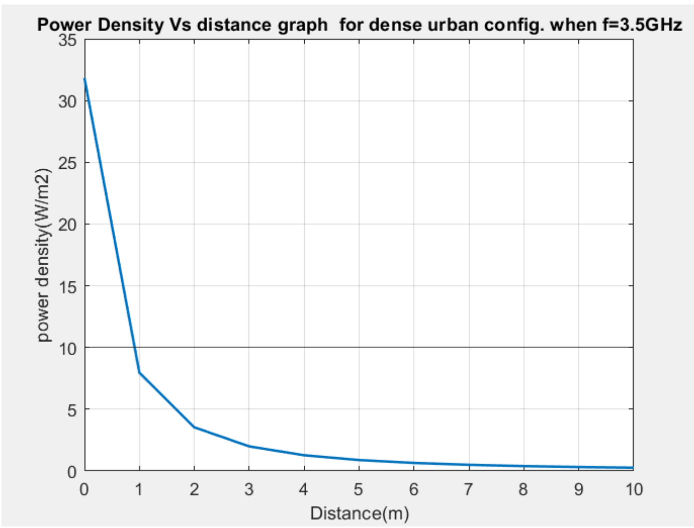

Figure 20 Power density Vs Distance graph for Typical Dense Urban Conf. when f=3.5GHz

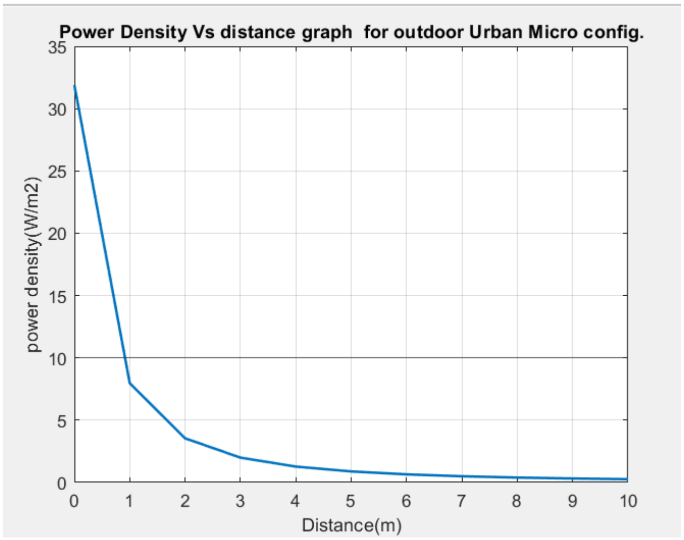

Figure 21 Power density Vs Distance graph for Urban Micro Conf. when f=4200MHz

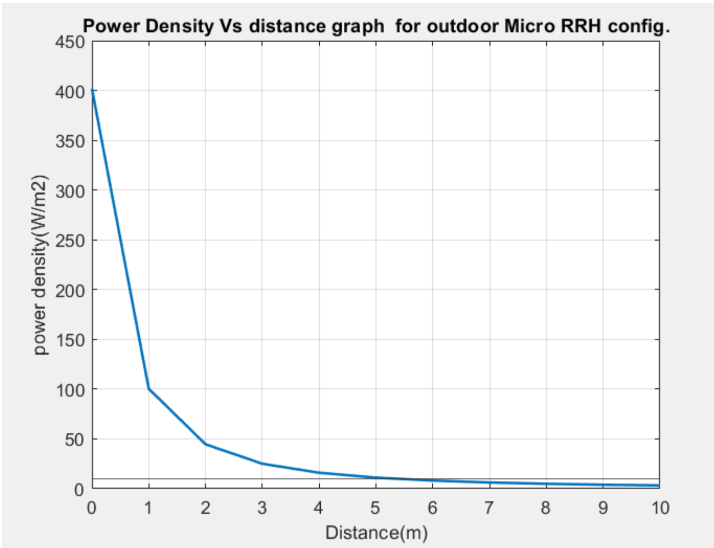

Figure 22 Power density Vs Distance graph for Micro RRH Conf. when f=4200MHz

Figure 18 shows the power density vs distance graph for a typical indoor hotspot scenario for 4 transmitters. Each transmitter has 250mW and it has a total of 1000mW power. when operating frequency is 3.5GHz. here it starts from 0.08W/m^2 and when the distance is increasing power density is decreasing. As per the ICNIRP guideline, the maximum power density value is 10W/m^2 and this scenario values are below the limit value.

Figure 19 shows the indoor hotspot power density assessment at frequency 26GHz. Here it starts from the 50.79W/m^2. This graph is also for the two transmitters with each 1.6W. It has a total of 3200mW. Until 1.4m, the power density is above 10W/m^2 and exceeds the guidelines' maximum limit values. So there should be a minimum distance between the transmitter and the general public. So as per the above Figure 19, the minimum distance is 1.4m for the indoor hotspot scenario when the operating frequency is 26GHz.

In the dense urban scenario, the graph shows the power density changes for four transmitters. Each transmitter has a power output of 10W, for a total output of 40W. It starts at 31.83W/m2, and as the distance increases, the power density values decrease. At 0.9m, the power density is equal to the 10W/m^2, and therefore the minimum distance for this scenario is 0.9m.

Figure 21 shows the Urban Macro configuration scenario. Here the graph shows the power density changes for four transmitters. Each transmitter has 2W and in total it has 8W power. Until 0.9m, the power density values are above the lit value and for this scenario also the minimum distance is 0.9m.

In the Micro RRH scenario, the graphs start with the power density of 400W/m^2. The graphs show the power density for four transmitters with each 20W. at the distance of 5.5m, it is equal to the limit value, and therefore the minimum distance between the transmitter and the general public is 5.5m. This type of transmitter is placed on the mast of the rooftops.

6.7. Power density assessment for co-located transmitter

The base station transmitters in the frequency bands 700MHz, 1800MHz, and 3.5GHz were co-located and we assume that the general public is in the cell radius of 198m distance power density was calculated to analyze the EMF exposure by the co-located transmitter. To calculate the power density for different frequencies, the power density for each frequency was calculated first, and then the three power densities were added in a second step.

P_density(from co-located transmitter) = **0.0026W/m^2**

If the general public is in the cell radius distance from the three transmitters, total power density,

P_density from three transmitter = 0.0026*3 = **0.0078W/m^2**

In this simulation co-located transmitters with the frequency bands 700MHz, 1800MHz, and 3.5GHz were considered and the power density was analyzed with the distance. for this simulation parameters of the table (16) were considered.

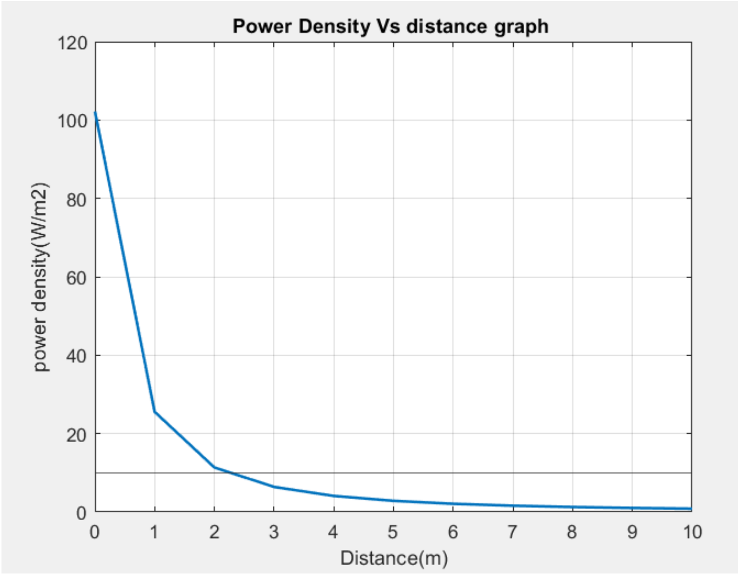

Figure 23 Power density Vs Distance graph for co-located transmitter

According to the above simulation results, the antenna power density decreases as the distance increases. It begins with a high-power density value and continues to have a higher value than the regulations' limit value for the general public until it reaches 2.2m. The maximum exposure value for the general public, according to the ICNIRP guidelines, is 10W/m2, as shown by the straight line in the graph above. So, it exceeds the exposure limit value until 2.2m. That means the minimum distance between the co-located transmitter and the general public is 2.2m.

7. DISCUSSION

In this thesis, EMF exposure was analyzed when deploying the 5G network. For this research power density assessment was used to analyze the exposure of the general public. In the first part of this thesis, we investigated EMF,5G, and the characteristics of 5G which are relevant to the EMF. After that, the regulations related to Human Exposure to EMF were analyzed and a comparison of the regulation was done with the key parameters for selected countries. By simulation, we analyzed how this regulation impacts the 5G deployment. EMF assessments were done for different frequencies, different environmental scenarios, different scenarios of typical 5G networks, and co-locating transmitters.

To protect the people from this EMF exposure guidelines were issued in terms of SAR, electric and magnetic field strength, and power density according to the frequency ranges. When comparing these regulations and guidelines globally, regionally, and in some selected countries such as Finland, USA and UK we can see that to minimize EMF exposure for the general public in addition to the global regulations, regionally and country-wise they published their own regulations. These regulations are not the same as global regulations and by their own regulations, they try to protect the general public from EMF exposure.

The ICNIRP, the European Council, and Finland have all concluded that the limit values for the incidence E-field, H-field, and power density at frequencies ranging from 400 to 2000 MHz should be the same. On the other hand, the ICNIRP guideline for the frequency range of 2-300GHz did not include any restriction values for the incident E-field strength or the incident H-field strength. Despite this, the incident power strength values that were determined by the ICNIRP, the European Council, and Finland are all equal to $10W/m^2$. Only the limit values up to 100GHz were published in the United States, and there were no limit values for the incident E-field strength or incident H-field strength for the frequency range of 1.5-100GHz. These limits only applied to the higher frequencies. Nevertheless, there is a value for the incident power strength that is equivalent to the values given by the ICNIRP, the European Council, and Finland for the incident power strength. The ICNIRP recommendation is also referred to by the United Kingdom for the general public, and the limit levels remain the same.

Matlab simulation was used to analyze the impact of EMF exposure in 5G deployment, and we analyzed this EMF impact on the general public using two methods: minimum distance calculation and power density assessment. As per the simulation results in the dense urban area at the frequency 3.5GHz, we can see that as per the regulation and guidelines the minimum distance between the transmitter and the general public is 0.3m. In this section, we look at the EMF exposure assessment from a single transmitter. However, when the simulation results of a typical 5G network in a dense urban area are considered, this distance is 0.9m. However, in this scenario, the transmitter power is for four transmitters, and the minimum distance is 0.9m according to the guidelines. There should also be a minimum distance of 1m between the rural area, urban macro mMTC, and urban macro URLLC. However, in these scenarios, the height of the transmitter antenna in the rural area is 35m, and the height of the transmitter antenna in the urban macro mMTC and urban micro URLLC is 25m. The rural and urban macro mMTCs operate at 700MHz, while the urban micro URLLCs operate at 4GHz. Here we considered maximum power values and it shows the worse cases. So practically to overcome this minimum distance from the general public the transmitters can be placed in towers, poles, roof-mounted structures, or as small cells providing localized coverage. Because as per the graphs we can see that when the general public is move away from the transmitter, the exposure is decreasing. These base station transmitters typically operate at lower power than in these worse cases. Also, before deploying the network, this minimum distance should be calculated and these areas should be included as a restricted areas that the general public cannot access.

The simulation always used maximum values of the simulation parameters of the transmitters. Therefore, with this maximum value, the maximum safety distance is calculated. When considering the simulation performance of a typical indoor scenario at a millimeter-wave there is a minimum distance of 1.4m. That means there should be a 1.4 minimum distance between the transmitter and the general public. For this simulation maximum transmitter power and the gain were considered and therefore 1.4m is the worst-case distance. but practical scenarios these values are lower values than simulated parameter values and therefore this distance can be changed. If the transmitter has high power these transmitters are placed on a high ceiling roof or roof nearly 10m high. In this situation to densify the network, it is needed to reduce the transmitter power to a lower value. On the other hand, in the indoor scenario, there can be lots of obstacles and providers need to place more transmitters to transmit the data with these obstacles.

There should be a consideration for a minimum distance to minimize exposure when the transmitters are co-located, and high towers or buildings can be used to minimize this. The general public should be kept at least 2.2 meters away from the transmitter, according to the simulation results. In this simulation, only three frequency bands were used: 700MHz, 1800MHz, and 3.5GHz. So, if multiple network operators use the same tower for transmission, they should consider the EMF exposure from the tower to the general public and calculate the minimum distance before deploying the network.

In this research, we used power density as a parameter to analyze EMF exposure. But as a future direction for this research, I would like to suggest the following research idea to analyze the EMF exposure by 5G.

1. Analyze the EMF exposure considering the uplink of the 5G network.
2. Analyze the EMF exposure in 5G by considering the different parameters except for the power density and SAR.

8. SUMMARY

EMF radiation is a moving electrical and magnetic field that travels in the form of an electromagnetic field through a medium (EMF). With the introduction of new generations of mobile networks, such as 2G, 3G, 4G, and 5G, it has been raised whether the electromagnetic field radiation (EMF) emitted by mobile wireless networks has any health or safety implications. When it comes to EMF's impact, it can only raise body temperature. People are concerned about EMF exposure because 5G uses high frequencies, such as above 6GHz, and a large number of transmitters. As a result, because they serve a small geographic region, the access points or base stations are located quite close to humans. Furthermore, it deployed a large number of APs/BSs, and as a result, people believe that there is a greater risk of exposing humans to EMF generated by downlink.

EMF has not been proven to cause brain tumors or cancer. The main mechanism of interaction between the RF-EMF and the human body is increasing body temperature by heating tissues. There are guidelines and regulations in place to limit EMF exposure caused by rising body temperatures. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published rules based on global considerations, with these limits defined in terms of specific absorption rate (SAR), electric and magnetic field strength, and power density per frequency band. Regarding the frequency bands, the European Council published rules and regulations for European countries. In this study, we looked into the country-specific regulations in a few countries. Then we compared Finland's, the United States', and the United Kingdom's national regulations to global and regional regulations. According to this comparison, in order to reduce EMF exposure for the general public, they published regional and national regulations in addition to global regulations. When we compare the guidelines, we can see that the limit values for the incidence E-field, H-field, and power density at frequencies ranging from 400 to 2000 MHz in the ICNIRP, European Council, and Finland EMF guidelines are the same. In addition, the ICNIRP guideline contains no limit values for incident E-field strength or incident H-field strength. In addition, for the frequency range of 1.5-100GHz, there were no limit values for incident E-field strength or incident H-field strength. For the simulation, two methods were used to assess EMF exposure: calculate the minimum distance and power density assessment. To assess EMF exposure, simulations were run for various frequencies(700MHz,1800MHz, and 3.5GHz), different environmental scenarios (indoor hotspot, dense urban, rural, urban macro mMTC, urban micro URLLC), and different scenarios of typical 5G networks (indoor hotspot, dense urban, micro, micro RRH).

When considering the simulation results with the different frequencies, the EMF level which is obtained from the simulation graphs did not cross the current exposure guidelines and limitations. According to the results of the simulations of dense urban, rural, urban macro mMTC, and urban micro URLLC, there is a minimum distance between the transmitter and the general public. Additionally, there is a minimum distance between the transmitter and the general public is the result of an indoor hotspot, dense urban, micro, and micro RRH scenarios in the typical 5G network. The power density was assessed by co-locating transmitters with frequencies of 700MHz, 1800MHz, and 3.5GHz, and the simulation results show that there is also a minimum distance between the co-located transmitter and the general public.

According to the simulation results, there is an EMF exposure near the transmitter in some scenarios such as dense urban, rural, urban macro mMTC, and so on. As a result, when deploying 5G networks in these conditions, EMF constraints and guidelines should be taken into greater consideration, and deployment should be carried out to minimize this exposure. As a result, before deploying the 5G network, the EMF exposure should be assessed in accordance with the guidelines and limitations by calculating the minimum distance or analyzing the power density. If there is EMF exposure, that area should be designated as restricted and inaccessible to the general public.

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10. APPENDICES

Appendix 1 Calculating the minimum distance

```
clear;clc;

% parameters

f=3.5*10^9; % operating frequency
c=3*10^8;
EIRP = 41;
G_tx = 6; %transmitter gain dBi
P_tx = 35; %dBm
G_rx = 0;
lamda=(3*10^8)/f;
h_tx =6; % micro transitter antenna hight
h_rx = 1.5; % receiver antenna hight
d0=1;
L_tx=0; %cable loss
receiversensitivity= -78;


e=input('Enter type of environment(1-UMa-LOS , 2-UMa-NLOS , 3-UMi.S.C-LOS , 4-
UMi.S.C-NLOS , 5-UMi.O.C.LOS, 6-UMi.O.S-NLOS ):');

FSPL = 20*log10((4*pi*f)/c);%Free space pathloss

EIRP = P_tx +G_tx - L_tx;%EIRP  power

%Link budget estimate
PL = EIRP-receiversensitivity+G_rx;

if e==1
   n=2;
   SF=4.1;
elseif e==2
   n=3;
   SF=6.8;
elseif e==3
   n=1.98;
   SF=3.1;
elseif e==4
   n=3.19;
   SF= 8.2;
elseif e==5
   n=1.85;
   SF = 4.2;
else
   n=2.89;
   SF=7.1;
end
```

```
X=(PL-SF-FSPL);
Y= 10*n;
Z=X/Y;

d=10.^(Z);
disp(d);


A=P_tx;
B=(10.^(G_tx/10));
EIRP_fordistance= A.*B;

%------%distance calculation-------

gamma=0.6;%reflection coefficient

%maximum transmission time

T=6;%if transmitter transmit x minutes in any thirty minutes period
t=(T/30);
lamda=(3*10^8)/f;
Y=lamda/(2*pi);%reactive near field boundary
p1=EIRP_fordistance*t; % average radiated power
p0=10%5G Referance level for power density accodrding to the INCIRP Guideline

% calculating the minimum distance

 D = max(sqrt(p1*((1+0.6)^2)/(p0*4*pi)), lamda/(2*pi))
 disp(D);

 %calculating one transmitter coverage area
 A= d.^2 * pi;
 disp(A);

 % NO. of required cells
 A_squrekm= A /10.^6;
 noofcells = 1/A_squrekm;
 disp(noofcells);
    .
```

Appendix 2 Power Density Calculation for Co-locating Transmitters

```
clear;clc;

% parameters

f_1=3.5*10^9; % operating frequency Hz
f_2=700*10^6;
f_3=1800*10^6;
c=3*10^8;

G_tx1 = 6; %transmitter gain dBi
G_tx2 = 15;
G_tx3 = 18;

P_tx1 = 35; %dBm
P_tx2 = 23;
P_tx3 = 43;
G_rx1 = 0;
G_rx2= 0;
G_rx3= 0;
d=197.64;

%power in watta
P_W1= (10.^(P_tx1/10))/1000;
P_W2= (10.^(P_tx2/10))/1000;
P_W3= (10.^(P_tx3/10))/1000;
%P_W4= (10.^(P_tx4/10))/1000;

%Gain in liner
G_L1=10.^(G_tx1/10);
G_L2=10.^(G_tx2/10);
G_L3=10.^(G_tx3/10);
%G_L4=10.^(G_tx4/10);

%power density in (W/m^2)

P1_1= P_W1.*G_L1;
P2_1= P_W2.*G_L3;
P3_1= P_W3.*G_L3;
%P4_1= P_W4.*G_L4;


P1_2 = 4.*pi.*d.^2;
P2_2 = 4.*pi.*d.^2;
P3_2 = 4.*pi.*d.^2;
%P4_2 = 4.*pi.*d_4.^2;

P_density_1 = P1_1/P1_2;
```

```
disp(P_density_1);
P_density_2 = P2_1/P2_2;
disp(P_density_2);
P_density_3 = P3_1/P3_2;
disp(P_density_3);


%total power density from the three transmitter
P_total =P_density_1 + P_density_2 + P_density_3;
disp(P_total);
```

Appendix 3 Power Density assessment for different scenarios

```
clear;clc;

% parameters

f=700*10^6; % operating frequency
c=3*10^8;
G_tx = 8; %transmitter gain dBi
P_tx = 49; %for 20MHz bandwith dBm
G_rx = 0;
lamda=(3*10^8)/f;
h_tx =35; % macro transitter antenna hight
h_rx = 1.5; % receiver antenna hight
d0=1;
L_tx=0; %cable loss

d_range=1:10;
for d=1:length(d_range)
%power in watta
P_W= (10.^(P_tx/10))/1000;

%Gain in liner
G_L=10.^(G_tx/10);


%power density in (W/m^2)

P_1= P_W.*G_L;
P_2 = 4.*pi.*d.^2;
P_density = P_1/P_2;


%total power density from the three transmitter
P_total(d) =P_density;
disp(P_total);
end
 %% Plotting t

figure;
plot(d_range, P_total,'LineWidth',1.5)
hold off
grid on
xlabel('Distance(m)')
ylabel('power density(W/m2)')
title('Power Density Vs distance graph for Rural Area')
yline(10,'-');
```