MAKERERE UNIVERSITY

ANALYSIS OF HUMAN EMF EXPOSURE IN 5G CELLULAR SYSTEMS

RONALD ISAIAH MPAWULO
17/U/569

A Final Year Project Report submitted to Makerere University in partial fulfilment of the requirements for the award of BSc in Telecommunications Engineering

Declaration

No portion of the work in this document has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

I have abided by the Makerere University academic integrity policy on this assignment.

Signature: ....
RONALD ISAIAH MPAWULO

Date: ....17/02/2022....

Approval

This report has been submitted for examination with the approval of supervisors.

Main-supervisor: Dr. Jonathan Serugunda
Head of Department/Lecturer
Department of Electrical and Computer Engineering, Makerere University

Signature: .... **Date:** 21/02/2022

Co -supervisor: Ms.Dativa Tizikara
Lecturer
Department of Electrical and Computer Engineering, Makerere University

Signature: .... **Date:** 28/2/2022

Dedication

I dedicate this report to all individuals that is parents ,lecturers, teachers,family, friends and colleagues that have supported me in my academic journey. May the good Lord bless you and reward you abundantly.

Acknowledgment

I would like to thank the Almighty God for his great providence with a healthy life, a healthy mind and wisdom that were key in carrying out this project.
Secondly , great appreciation goes to my supervisors , Dr Jonathan Serugunda and Ms Dativa Tizikara for the help and guidance rendered during carrying out this project. I also thank my project partner David Kasamba for his tireless efforts in ensuring this project is a success.
Lastly, I appreciate the administration and staff of the Department of Electrical and Computer Engineering for this great opportunity to work on this project.

Abstract

The project investigates human EMF exposure in 5G cellular systems in the downlinks through obtaining the range of possible Power Densities and Specific Absorption Rates. To do this, different 5G deployment scenarios (5G UMi, 5G UMa and 5G Indoor) are-modelled and simulated using NYUSIM simulator. Also with the same simulator, a 4G cellular system is modelled and simulated.
Different values of the received power at the UEs are obtained and an average at each of the distances is computed. Using the Average Received Power values, Power Density and SAR in each of the scenarios is obtained. A comparison between the 4G and 5G systems is made. Also a check was to find whether the PD and SAR are within the ICNIRP guidelines in terms of SAR and PD.
The findings showed that SAR in 5G (especially 5G UMi and 5G indoor) was way higher as compared to 4G. However, the current ICNIRP guideline of not exceeding 2W/kg is for the frequency range of 10-10,000 MHz. No limit in terms of SAR has been set for frequencies higher than this. However, taking this limit into consideration, it was found that this limit is exceeded for close BS-UE separation.
Two mitigation protocols were proposed (one for indoor and the other for outdoor) that could help minimize exposure in terms of SAR and also not to exceed a limit of 2W/kg. The indoor protocol is based on power control and the outdoor protocol puts emphasis on SAR shielding. Also the effect of this mitigation on data rates was found which was a slight reduction
The results obtained show that there is need for regulations for down links in terms of SAR at higher frequencies such as 28 GHz for outdoor and 60GHz for indoor.

List of Figures

List of Tables

List of Abbreviations

4G	Fourth Generation
5G	Fifth Generation
BS	Base Station
AP	Access Point
D2D	Device to Device
EMF	Electromagnetic Field
FDD	Frequency Division Duplexing
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
mm-W	Millimeter Wave
P2P	Peer to Peer
PD	Power Density
RF	Radio Frequency
Rx	Receiver
SAR	Specific Absorption Rate
TDD	Time Division Duplexing
Tx	Transmitter
UCC	Uganda Communication Commission
UMa	Urban Macro
UMi	Urban Micro
UE	User Equipment
WHO	World Health Organization
Wi-Fi	Wireless Fidelity

Contents

Chapter 1
Introduction

This chapter gives the Project Background, Problem Statement , Justification, Purpose of the Project, Objectives and the Project Scope.

1.1 Project background

5G is the fifth generation technology standard for cellular networks, which cellular phone companies began deploying in 2019.It is a planned successor to the 4G networks which provide connectivity to most current cellphones. Like its predecessors, 5G networks are cellular networks, in which the service area is divided into small geographical areas called cells. All 5G wireless devices in a cell are connected to the Internet and telephone network by radio waves through a local antenna in the cell.

5G has greater bandwidth, giving higher download speeds, eventually up to 15 to 20 gigabits per second. The increased bandwidth enables the new networks to be used as general internet service providers for laptops and desktop computers, competing with existing internet service providers such as cable internet and also will make possible new applications in internet of things and machine to machine areas

5G communication technology mobile networks have been implemented in some countries and yet to be implemented in others as a result of the increasing demand for higher data rates and uninterrupted reliable service. This has raised concerns since the communication is at a frequency spectrum above 6 GHz[1]so as to ensure higher data rates, low latency, massive connectivity, network reliability and energy efficiency.

With 5G,there is exploration of the underutilized millimeter wave (mm-wave) spectrum for future broadband communication networks whose frequencies range from 6GHz to 300 GHz. With this technology, a large number of transmitters will operate at the base stations and in addition, narrower beams will be used as a solution to for higher attenuation at higher frequency bands[2] .

The higher data rates necessitate a higher signal power at the receiver and this results and this results in a concern in the increase in the EMF energy imposed to the human user [3]. Also with Access Points (Base Stations) serving a small geographic area hence closer to humans and with a larger number of base stations deployed, it will lead to a higher chance of human exposure to EMFs generated by down links. These characteristics of

5G networks have developed controversies among researchers on whether the technology possesses a risk to human health[4].

1.2 Problem statement

5G targets to operate at a higher frequencies above 6 GHz. This will result into availability of far wider band widths than the earlier cellular standards (2G, 3G and 4G). Also there is need of integrating a large number of miniaturized antennas in small directions attributed to very small wave lengths [5].
A high gain directional antenna array is used and this enables radiation energy to be focused in a certain direction leading to an increased amount of EMF energy deposition in the main lobe towards a human body in addition to base stations serving small geographical region hence more chance of exposure to EMF radiations due to this close proximity [6].Studies show that long-term exposure to high EMFs is likely to impose damage to biological tissues. In fact, WHO's International Agency for Research on Cancer (IARC) has classified RF fields as possibly carcinogenic to humans [7]

1.3 Justification

There is public concern about the negative impact of radio frequencies on human health as a result of future implementation of the 5G infrastructure which is expected to increase EMF exposure to humans. Also, some members of society are frightened that 5G will expose the population to new sources of dangerous radio frequency radiation after installation of the multiple base stations.
Therefore, effective measurements of electromagnetic fields are essential for both, the deployment of 5G networks and their later operation. Proper measurement methodology will enable monitoring of the EMF intensity, allowing government bodies as well as local communities to control whether EMF exposure value levels are safe to humans and the environment as a whole

1.4 Significance of the Project

This project aims at investigating possible EMF exposure levels from 5G Cellular systems. It entails finding EMF exposure levels for human users at different distances from Access Points / Base Stations

Through the project, values of the Power Density (PD) and Specific Absorption Rate (SAR) shall be found at different distances and these compared with the limit set by the International Commission for Non Ionizing Radiation Protection (ICNIRP) and other bodies such as the FCC.

Also another purpose is to compare the Human EMF Exposure existing 4G Cellular Systems in Uganda and the 5G Cellular systems yet to be deployed here and hence analyze how the two relate as regards Exposure levels.

Another purpose is to provide recommendations as regards deployment of 5G Cellular systems in a way that will ensure safety to humans

1.5 Project Objectives

1.5.1 Main objective

- To investigate human EMF exposure in 5G cellular systems.

1.5.2 Specific objectives

- To model and simulate different 5G deployment scenarios.
- To determine PD and SAR from the 5G deployment scenarios.
- To determine PD and SAR in existing 4G systems
- To compare PD and SAR of 4G and 5G systems and provide recommendations.

1.6 Project Scope

The project focuses on EMF exposure from 5G down-links.
The analysis bases on finding PD and SAR from 5G deployment scenarios (5G UMi, 5G UMa and 5G Indoor) and comparing these values with those from 4G. A check on how the PD and SAR relate with the guidelines set by ICNIRP is done and recommendations given.

1.7 Chapter Summary

The chapter above shows the necessity and rationale of the project. It contains the Problem Statement, Justification,Significance of the Project,the Objectives and Project Scope.The objectives stated are obtained in Chapter 3 and Chapter 4.

Chapter 2

Literature review

This chapter contains the notes reviewed on 5G Network Technologies,use of mm-Wave Spectrum, Electromagnetic Fields, PD and SAR as metrics for measurements, Guidelines put in place by FCC and ICNIRP as regards EMF Exposure ,Downlink Data Rates, The 5G Appeal, Recent Work and Our Contributions

2.1 5G Network Technologies

5G supports the following technologies that make it better and more reliable than the earlier technologies.

1. Massive MIMO
   In massive MIMO, hundreds of antennas serve tens of user terminals in one single frame[8].
2. Ultra-Dense Network
   The network comprises of very many devices and computers connected operating at the same time.
3. Millimeter-wave operation
   The underutilized millimeter wave spectrum is used to ensure wider bandwidths and faster speeds to support the network.

2.1.1 Utilisation of the mm-wave spectrum

As fifth-generation (5G) is developed and implemented, the main differences compared to 4G are the use of much greater spectrum allocations at untapped mm-wave frequency bands, highly directional beamforming antennas at both the mobile device and base station, longer battery life, lower outage probability, much higher bit rates in larger portions of the coverage area, lower infrastructure costs, and higher aggregate capacity for many simultaneous users in both licensed and unlicensed spectrum (e.g. the convergence of Wi-Fi and cellular)[9].

The backbone networks of 5G move from copper and fiber to mm-wave wireless connections, allowing rapid deployment and mesh-like connectivity with cooperation between base stations.

Also, base station-to-device links use mm-waves in addition to back-haul links between base stations. These are able to handle much greater capacity than today's 4G networks in highly populated areas.

Mm-Wave carrier frequencies allow larger bandwidth allocations, which translate directly to higher data transfer rates. Mm-wave spectrum would allow service providers to significantly expand the channel bandwidths far beyond the present 20 MHz channels used by 4G customers[9]. By increasing the RF channel bandwidth for mobile radio channels, the data capacity is greatly increased, while the latency for digital traffic is greatly decreased, thus supporting much better internet-based access and applications that require minimal latency.

Due to operation in the mm-wave spectrum, the high frequencies are subject to attenuation in a small range. To overcome this signal loss two approaches are used and these are massive MIMO base stations and small-cell access points.

For massive MIMO, base stations allocate antenna arrays at the existing macro base stations, which can accurately concentrate transmitted energy to the mobile users [10]. Small cells offload traffic from base stations by overlaying a layer of small cell access points, which decreases the average distance between transmitters and users, resulting in lower propagation losses, higher data rates, and energy efficiency.

These important trends are readily supported and are enhanced by the mm-wave spectrum since the tiny wavelengths allow for dozens to hundreds of antenna elements to be placed in an array on a relatively small physical platform at the base station or access point. The evolution to small cells ensures that mm-wave frequencies overcome any attenuation

2.2 Electromagnetic fields

Electromagnetic field is a property of space caused by motion of electric charges. When a charge is place, an electric field surrounds it. If the charge is set into motion, it results into a magnetic field. Also, a changing magnetic field can result into a magnetic field. The co-existence of the two fields results into an electromagnetic field.

Electromagnetic fields exist naturally in our environment. They are produced by the electric charges in the atmosphere associated with thunderstorms. Also, the earth possesses a magnetic field and hence the existence of the North and South poles. Human made sources of Electromagnetic fields include electricity flow from wires, cables and sockets resulting into low frequency Electromagnetic fields. However, the main source of Electromagnetic fields in our environment is wireless communication that necessitates signal flow through the atmosphere/environment.

2.2.1 Effect of Electromagnetic Fields on the Human Body

Exposure to artificial electromagnetic fields has been steadily increasing steadily over the past years and everyone is exposed electric and magnetic fields due to activities such as the generation and transmission of electricity, domestic appliances and industrial equipment and telecommunications and broadcasting.

The human body has tiny electric currents flowing through it even in the absence of external electric fields and this is due to chemical reactions that occur within the human body. Just like how EMFs influence any other material made up of charged particles. i.e influence the distribution of electric charges at their surface they influence the human body in a similar manner as they cause current to flow through the body to the ground. The strength of the current depends on the intensity of the outside magnetic field and if it is sufficiently large, this current flow could cause stimulation of nerves and muscles or affect other biological processes.

However, heating is the main biological effect of the electromagnetic fields of radio frequency fields. It is the heating effect of the radio frequency fields that is a basis of the current guidelines. Research is still undergoing on how exposure below the threshold level for body heating could affect the body in a long-term though to date, no adverse health effects from low level, long-term exposure to radio frequency or power frequency fields have been confirmed.

2.2.2 EMF Exposure from the mm Wave Spectrum in which 5G operates.

Mm-wave radiation is non-ionizing because the photon energy is not nearly sufficient to remove an electron from an atom or a molecule.

However, from a safety point of view, research on mm-wave biological effects is necessary for accurately evaluating the potential health hazards related to mm-wave exposure and for developing and updating safety standards for the mm-wave regime.

The mm-wave band is the part of the RF spectrum between 30 and 300 GHz that corresponds to a free space wavelength ranging from 10 to 1 mm.

Taking the particle-like nature [10] perspective of mm-waves, they constitute of photons with each photon having an energy level given by,

$$E = hf = \frac{hc}{\lambda} \tag{2.1}$$

where h is Planck's constant ($h = 6.626 \times 10^{-34} Js$ or $(4.135 \times 10^{-15} eVs)$, and c is the speed of light $(3 \times 10^{8} m/s)$,and λ is the wavelength (m) of the radiated signal

Mm-wave radiation is non-ionizing because the photon energy is not nearly sufficient to remove an electron from an atom or a molecule (typically 12 eV is required) [11].

Thus, at mm-wave frequencies, the photon energy is more than four orders of magnitude weaker than ionizing radiation and is thus not capable of displacing electrons, which disrupts molecular bonds; this disruption is linked to cancer [12].

The major biological effect caused by the absorption of electromagnetic mm-wave energy is heating of the biological tissues, cells, and biological fluids. However, communication systems are expected to comply with exposure guidelines to prevent any adverse health effects related to the thermal effects.

2.3 ICNIRP and FCC Guidelines

5G deployment is the new trend of communication technology that has been embarked on. Its deployment has taken on in various countries such as South Korea, China, United States of America and United Kingdom leading in setting up its deployment. In the near future, Uganda is also expected to deploy 5G technology on addition to existing technologies of 2G, 3G and 4G already in existence.

In the earlier technologies that is 2G, 3G, and now 4G, Uganda Communication Commission has been analyzing EMF exposure on human body. According to the National survey in 2015 on electromagnetic field (EMF) exposure around GSM base stations in Uganda, all results suggest that the exposure levels around the base stations in the country are a very small fraction of the public ICNIRP exposure reference levels [13].

The FCC and ICNIRP standards are designed principally to protect against thermal hazards.

A SAR value of 4 W/kg, averaged temporally and spatially over the whole body, was recognized as the key working threshold for harmful biological effects in humans. This was as a result of two behavior disruption experiments by de Lorge et al [14] [15].

In the two experiments, rats and monkeys were trained on an auditory-observing response task and the animals were exposed to RF radiation during their performance. The experiments concluded that disruption of behavior occurred when the animals were exposed to a SAR of approximately 4W/kg after 30-60 minutes of exposure and when the body temperature increased by 1 degree Celsius. [15].

Hence by a careful and extensive review of biological and scientific literature, the 4W/kg whole-body SAR is recognized as the working threshold for when RF energy begins to induce an undesired biological effect on humans [16].

For FCC, radiation restrictions between 100KHz and 6GHz use a safety factor of 10 to obtain a whole-body average SAR level of 0.4 W/kg for occupational exposure. An additional safety factor of five is introduced further to the general public giving a whole-body SAR limit of 0.08 W/kg.

Since SAR distribution differs from point to point in the human body, it is generally accepted that the maximal localized SAR could be as high as 20 times the whole-body averaged SAR [17]. Therefore a SAR level of 1.6 W/kg in 1g of tissue in the head and trunk, and 4W/kg in any 10g of tissue in limbs are adopted by FCC.

The ICNIRP guidelines are similar to those of the FCC, with a few exceptions. The maximum localized SAR limitation of the ICNIRP guidelines is chosen to be 2 W/kg in any 1 g of tissue in the head and trunk and 4 W/kg in any 10 g of tissue in the limbs over 6 min of exposure for frequencies up to 10 GHz for the general public.

1-g SAR provides finer resolution and thus offers a more conservative restriction on the actual energy allowed to be distributed in the tissue.

The guidelines by ICNIRP and FCC are as shown below [4];

Guideline	PD Restriction for General Public (W/m2)	Frequency Range (MHz)
ICNIRP	2	10-400
ICNIRP	f/200	400-2,000
ICNIRP	10	2,000-300,000
FCC	10	1,500-100,000

Table 2.1: Power Density Restrictions and the corresponding frequencies as per ICNIRP and FCC

Exposure Standard	SAR limit for RF Near Field Exposure (W/kg)	Frequency Range (MHz)
ICNIRP	2	10-10,000
FCC	1.6	0.1-6,000

Table 2.2: SAR limits for exposure and their corresponding frequencies as per ICNIRP and FCC

At mm-wave frequencies, energy absorption becomes increasingly confined to the surface layers of the skin, and the heating effect is directly related to the incident PD. Thus the PD and not the SAR is used as a basic restriction in the mm-wave exposure guidelines.

As seen from Table 2.1 and Table 2.2 , the exposure restrictions change from SAR levels to PD levels when moving to higher frequencies. This implies the restrictions change from evaluating volumetric energy distribution (SAR below 6Hz for FCC and below 10 GHz for ICNIRP) to planar energy distribution (above 6GHz and 10 GHz)[18]

Despite ICNIRP and FCC consider PD as a metric for the measurement of safety at frequencies higher than 10 GHz and 6GHz respectively [19, 20],a recent study suggested that the PD standard is not efficient to determine the health issues especially when devices are operating very close to the human body at very high frequencies.

2.4 Power Density and Specific Absorption Rate

Mainly there are two quantities used to measure the intensity and effect of human EMF exposure and these are;

i. Plane-Wave equivalent Power Density (PD)

ii. Specific Absorption Rate (SAR)

2.4.1 Plane-Wave Equivalent Power Density (PD)

Power density is the amount of power radiated per unit volume at a given distance. It can be obtained from [4];

$$PD(d) = \frac{[E(d)]^2}{\rho_0} \tag{2.2}$$

Where E(d)is the Electric field strength at a distance d and ρ_0 is the characteristic impedance of free space.
The power Density can therefore be expressed in terms of transmitter's parameters as;

$$PD(d) = \frac{P_T G_T(d, \phi)}{4\pi d^2} \tag{2.3}$$

Where P_T is a transmit power, G_T is a transmit antenna gain and d is a Base Station to User Equipment distance in meters.

2.4.2 Specific Absorption Rate (SAR)

Specific Absorption Rate is defined as a measure of the power absorbed per unit mass by a human body exposed to radio frequency (RF) electromagnetic field. Therefore SAR quantifies the rate at which the human body absorbs energy from an electromagnetic field. It is measured in W/kg.

SAR at a given point x can be expressed as [21];

$$SAR(x) = \frac{\sigma[E(x)]^2}{\rho} \tag{2.4}$$

Where σ is the conductivity of the material and ρ is the density of the material kg/m^3

SAR in terms of distance d which is also a function of ϕ for cellular communications can be expressed as;

$$SAR(d, \phi) = \frac{2PD(\phi)T(\phi)m(\phi)}{\delta\rho} \tag{2.5}$$

Where T is the power transmission coefficient, δ is the skin penetration depth in meters. The function m(ϕ) is dependent on the tissue properties of dielectric constant.

The same equation above at the point on the air-skin boundary as a function of PD(d,ϕ) can be re-written as;

$$SAR(d, \phi) = \frac{2PD(\phi)(1 - R^2)}{\delta \rho} \tag{2.6}$$

Where R is the reflection coefficient.

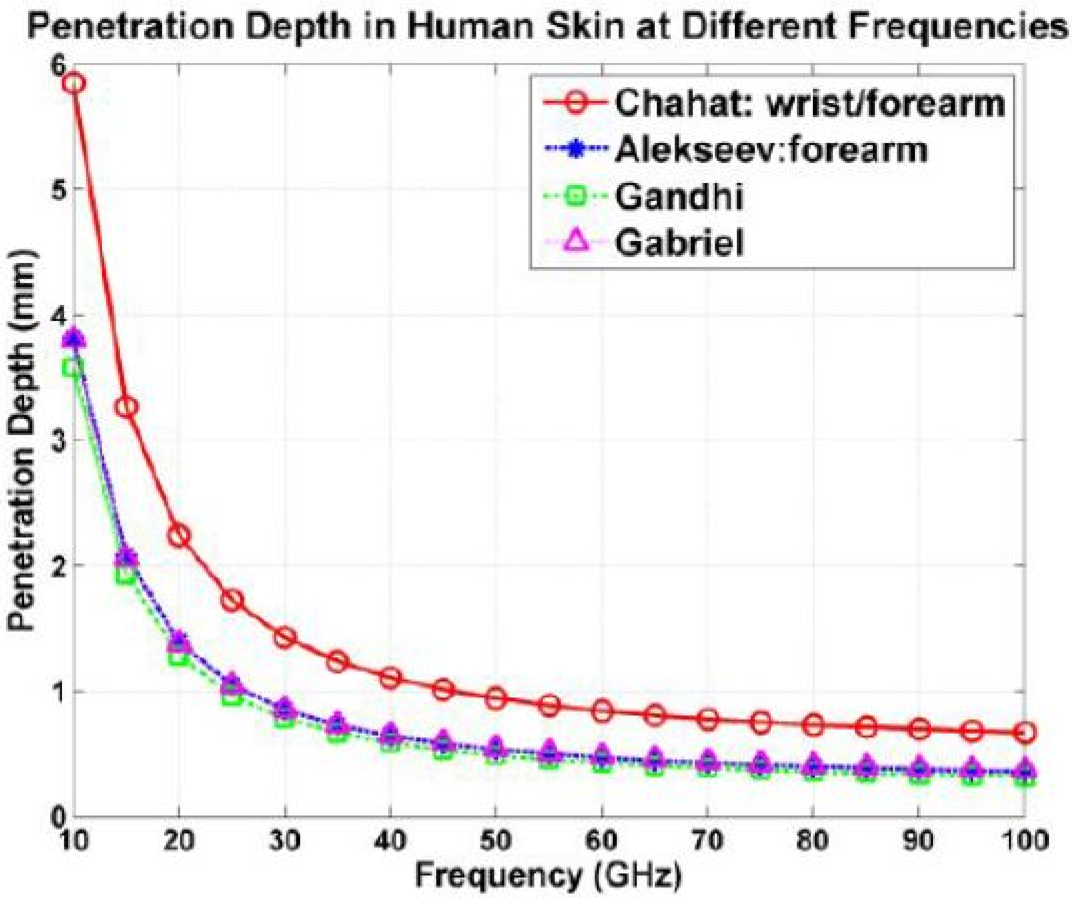

Figure 2.1: The penetration depth in the human skin with the increase of exposure frequencies using different skin models [26].

2.4.3 Comparison between PD and SAR

PD is not as useful as SAR in the assessment of safety since PD does not display the level of EMF energy that is actually that is actually absorbed in the body as SAR does. Recent studies on the analysis on EMF showed that there is no guideline set in terms of SAR in far-field exposure so far based on a belief that SAR does not have a significant effect on the human body in far-field [22].

Furthermore, research suggests that the human users in 5G will be exposed to higher SAR than the present systems at every point in a network due to use of many Access

Points in close range as to overcome attenuation at higher frequencies [10]. Hence, regulatory authorities to set SAR guidelines as majority of users will be in the near-field. As a result, ICNIRP came up with guidelines on SAR.

It is also noted that with millimeter-wave which is the spectrum in which 5G operates in order to obtain high data rates, the penetration depth into human tissue dramatically decreases compared to traditional cellular bands. Therefore, the incident power density is used as the dosimetric quantity of electromagnetic field (EMF) exposure instead of the Specific Absorption Rate (SAR)[23].

Both SAR and Power Density limits are set to prevent excessive surface temperature elevation at the human skin [24]. Therefore the main aim of the standards set by international bodies such as ICC and ICNIRP is to prevent excessive surface temperature elevation on the human body

The SAR values differ according to the kind of tissue taken into consideration. For instance, SAR value for tissues in the limbs is different than the SAR value for any tissue within the eyes. Also, SAR at the surface of the exposed tissue is different from the SAR deep within that exposed tissue[24]. However, unlike evaluations of SAR or temperature, evaluations based on PD do not rely on knowledge of the distribution of fields or power absorption in the tissues but only on the density of power traveling towards the tissue. Hence, PD is not likely to be as useful as SAR for assessing safety from cellular communications system According to International Commission on Non-Ionizing Radiation Protection (ICNIRP) the multiple-antenna system, which generates large antenna gain, imposes higher concentration of electromagnetic radiation energy gain and hence more exposure the human body.

2.5 The 5G appeal

A section of the scientific community – mainly doctors and researchers in medical sciences – argue that there are negative impacts from EMF exposure and that these will increase with the implementation of 5G. A 5G appeal [8]as presented to the United Nations in 2015 stating that with the increasingly extensive use of wireless technology, especially when 5G is deployed, nobody could avoid exposure to constant EMF radiation because of the huge number of 5G transmitters with an estimated 10 to 20 billion connections. In addition, the appeal states that a large number of scientific publications illustrate EMF exposure effects such as an elevated risk of cancer, genetic damage, learning and memory deficits, neurological disorders, etc.

The appeal recommends a moratorium on the deployment of 5G for telecommunications until potential hazards for human health and the environment have been fully investigated by scientists independent of industry. In this regard, some scientists consider it necessary to establish new exposure limits that take account of the new characteristics of exposure [25].

2.6 The Downlink Data Rates

To obtain the downlink data rates, Shannon's formula is used,

$$DownlinkDatarate = Blog_2(1 + SNR) \tag{2.7}$$

where B is the bandwidth, and SNR the Signal to Noise Ratio .

The Signal to Noise Ratio is evaluated from,

$$SNR = \frac{SignalPower}{NoisePower} \tag{2.8}$$

With consideration of White Nosie, The Noise Power is evaluated from;

$$NoisePower = kBT \tag{2.9}$$

Where k is Boltman's constant , B is the Bandwidth and T is the Temperature.

2.7 Related Work

2.7.1 Analysis of Human EMF exposure in 5G Cellular Systems by Imtiaz Nasim

In this research, analysis on exposure in downlinks was made and it was found that there was a higher received signal power that resulted into high PD and SAR values. An explicit comparsion based on the 3rd Generation Partnership Project was made.
The merits of of considering SAR in evaluation at even higher frequencies were stated despite earlier considerations of considering PD only.
As a remedy to potential threat to human health , downlink mitigation protocols for both indoors and outdoor were proposed[27].

2.8 Contributions

In this project, concentration was focused on the downlinks of 5G in comparison to majority of prior work that specifically investigates uplinks with focus on the devices used.

Both PD and SAR where analyzed despite the prior assumptions of FCC and ICNIRP of SAR being insignificant at high frequencies. The findings actually show that there is need to put guidelines in terms of SAR for high frequencies.

A comparison of EMF exposure in terms of both PD and SAR was made between 5G Systems and 4G Cellular Systems

Two mitigation protocols for SAR where proposed. One for 5G Indoor and the other for 5G Outdoor. The effect of the mitigation on the data rates was also evaluated.

2.9 Chapter Summary

This chapter shows the different literature consulted before and during the implementation of the project. This gave guidance on what to consider in implementing the project as regards modelling 5G networks and also prioritizing finding PD and SAR as the metrics for analysis.It highlights the available regulatory standards by FCC and ICNIRP and the basis of how the were set. Also recent work in this field and the contributions made are highlighted.

Chapter 3
Implementation

In this chapter, the methodology used in carrying out the project is done. The process of how the investigation of EMF Exposure was done is clearly described. It contains the considerations for the network simulations and how computations of PD and SAR were done

3.1 Modelling and simulating different 5G Deployment Scenarios

To model of 5G network, NYUSIM Simulator Software was downloaded and used.

NYUSIM open source provides complete statistical channel models and simulation code (in Matlab) for generating realistic spatial and temporal wide band channel impulse responses

.

NYUSIM has the following features for each modelling component:

1. Spatial Consistency
   This indicates realistic and continuous channel evolution along the User Terminal trajectory in a local area. It simulates spatially correlated channel impulse responses when a User Terminal moves in a local area or when multiple User Terminals are closely spaced. To achieve this, large scale parameters such as shadow fading, line of sight and Non line of sight conditions are generated. Time invariant small scale parameters such as angles, power, delay, phase of each Multimedia Personal Computer are generated. A geometry- based approach using multiple reflection surfaces is implemented to update spatially correlated and time variant angular information[28].

2. Human Blockage Shadowing
   NYUSIM can simulate human blockage shadowing loss due to a person near a mobile phone that may block the transmission link.

3. Outdoor- Indoor Penetration Loss
   Also NYUSIM can simulate channel responses with building penetration loss for the User Equipment inside a building. The penetration loss can become prominent at mm Wave frequencies.

3.1.1 Network Parameters used in the modelling

To use NYUSIM, input parameters input parameters were selected to use in the user friendly GUI

The input parameters are grouped as shown below [28];

i. 16 input Channel Parameters that define the propagation channel

ii. 12 input Antenna Properties that specify the TX and RX antenna arrays

iii. 10 input Spatial Consistency parameters

iv. 5 input Human Blockage parameters

v. 2 input Outdoor to Indoor penetration parameters.

The details of each of the input parameters are as shown below;

Channel Parameters

1. Distance Range Option,Operating Frequency
2. RF Band width
3. Scenario (UMi or UMa)
4. Environment (LOS or NLOS)
5. Transmitter- Receiver Separation Distance i.e.the upper bound and lower bound distance
6. Transmitter Power
7. Base Station Height
8. User Terminal Height
9. Number of Receiver Locations
10. Barometric Pressure
11. Humidity
12. Temperature
13. Rain rate
14. Polarization
15. Foliage loss(This could include Distance within Foliage and Foliage Attenuation)

Antenna Properties

1. Transmission Array Type
2. Number of Transmission Antenna Elements
3. Transmission Antenna Spacing in wavelength
4. Number of Transmission Antenna Elements per Row
5. Transmission Antenna Azimuth
6. Transmission Antenna Elevation
7. Transmitter Power
8. Receiver Antenna Type
9. Number of Receiver Antenna Elements
10. Receiver Antenna Spacing
11. Number of Receiver Antenna Elements per Row
12. Receiver Antenna Azimuth
13. Receiver Antenna Elevation

Spatial Consistency Parameters

1. Correlation Distance of Shadow Fading
2. Correlation Distance of LOS and NLOS condition
3. User Track type
4. Moving Distance
5. Segment Transitions
6. Update Distance
7. Moving Direction
8. User Velocity
9. Side Length (Only for Hexagon Track)
10. Orientation (Only for Hexagon Track)

Human Blockage Parameters

This could be put in the ON or OFF state.
A "Default Settings for Human blockage" is provided. If the user chooses "Yes", the transition rates and average mean attenuation are implemented based on a linear fit to the default data given and changes to fit the work in as the RX antenna azimuth changes. If the user chooses "No", the transition rates and mean attenuation are free to edit for user-specified preferences. [28]

Out Door to Indoor Parameters.

1. Penetration Loss (Yes/No)

2. O2I Loss Type (Low Loss/ High Loss)

Different values of the parameters were used to increase the accuracy and obtain a more realistic output of the results

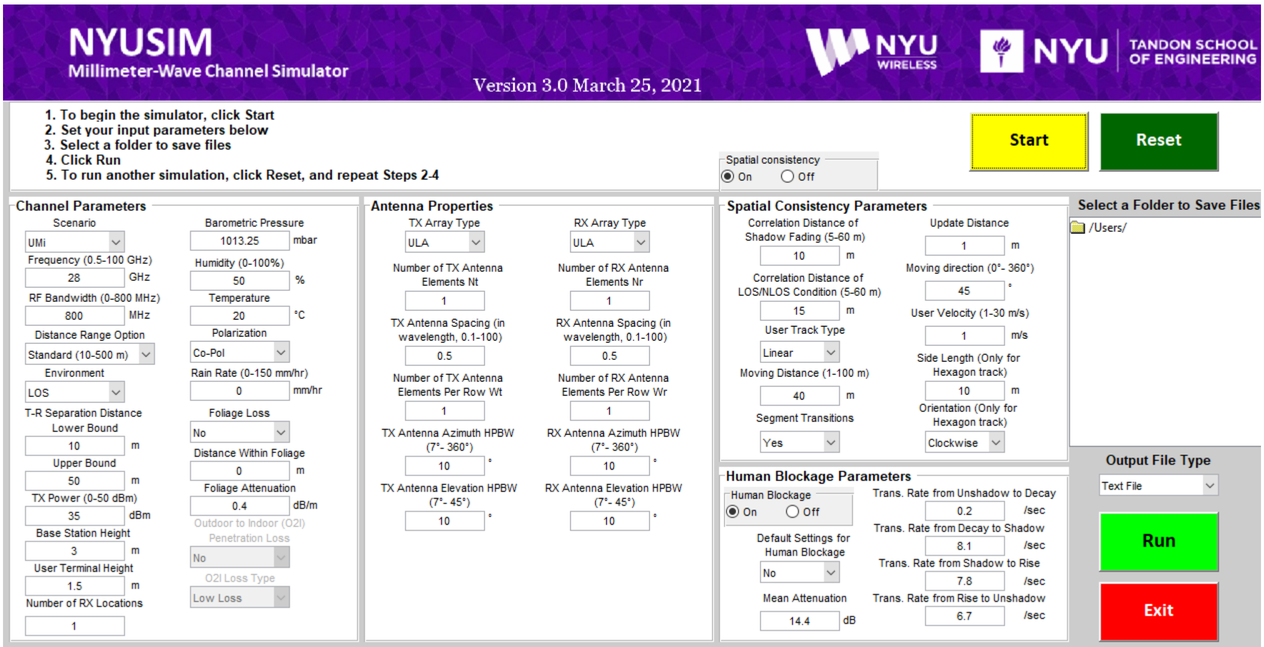

Figure 3.1: GUI of the NYUSIM software

3.1.2 The 5G Deployment Scenarios Modelled and Simulated with Associated Parameters

Out Door Scenarios

For Urban Micro- Line of Sight (UMi-LoS),The model involves micro cells with a small radius of approximately 200m. MIMO technique with concurrent transmitting and receiving from an antenna matrix composed with several hundreds of antennas was used. The UMi setup is for densely populated areas for example large cities where the density of UE is high

.

For Urbarn Macro-Line of Sight (UMa-LoS), The model involves macro cells with a radius of approximately 500m. Also here, MIMO technique with concurrent transmitting and receiving from an antenna matrix composed with several hundreds of antennas was used. The UMa setup is for less populated areas for example large cities where the density of UE is not that high.

Frequency spectrum of 28 GHz was used as a potential candidate for 5G NR. In our model, we use random UE positions with over 200 snapshots at each of the similar distances giving a total of over 200,000 total snapshots for all the random distances in each of the scenarios.

The network parameters are as shown in Table 3.1

	Parameter	**Value**
Channel Parameters	Distance Range Option(BS-BS)	200m (UMi) 500m (UMa)
	Operating Frequency	28 GHz
	RF Band width	800 MHz
	Environment	LoS
	Transmitter Power	35dBm
	Base Station Height	10m (UMi) 25m (UMa)
	User Terminal Height	1.5m
	Barometric Pressure	1013.25 mbar
	Humidity	50 percent
	Rain rate	0
Antenna Parameters	Transmission Array Type	ULA
	Number of Transmission Antenna Elements	4
	Transmission Antenna Spacing in wavelength	0.5
	Receiver Array Type	ULA
	Number of Receiver Antenna Elements	4
	Receiver Antenna Spacing in wave length	0.5

Table 3.1: Parameters of 5G UMi and 5G UMa

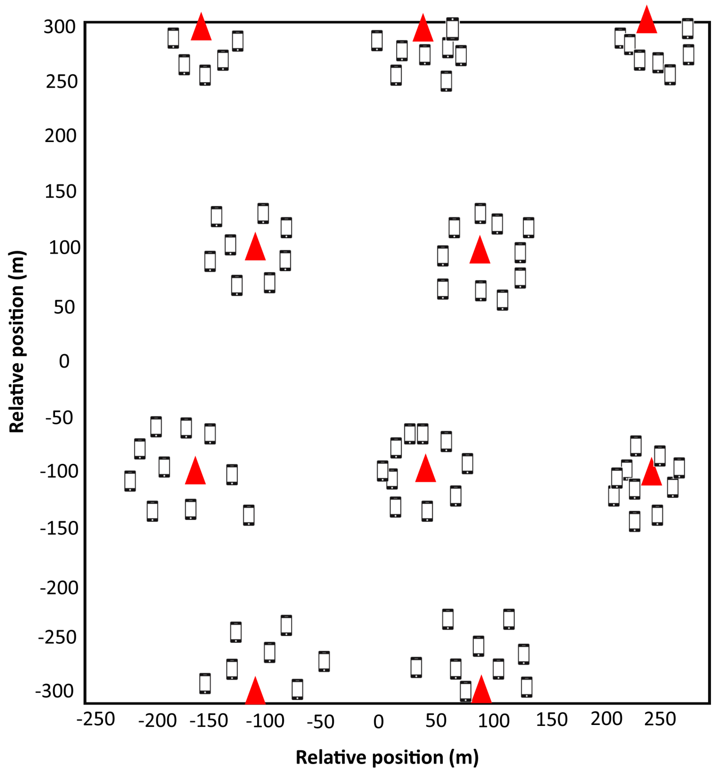

Figure 3.2: Base Station Set up for the 5G UMi

Indoor Scenario

The Indoor Scenario was modeled with the following parameters in Table 3.2,

	Parameter	Value
Channel Parameters	Operating Frequency	60 GHz
	RF Band width	800 MHz
	Transmitter Power	24 dBm
	Inter AP distance	20 m
	AP Height	3m
Antenna Parameters	Number of Transmission Antenna Elements	2
	Transmission Antenna Spacing in wavelength	0.5
	Number of Receiver Antenna Elements	2
	Receiver Antenna Spacing in wave length	0.5

Table 3.2: Parameters for the Indoor Scenario

3.1.3 Obtaining Power Density and Specific Absorption Rate

On running the simulation in each case, several outputs such as Received Power in dB, Path loss in dB and delay Spread in ns are obtained
These values are obtained for over 200 snapshots at each of the distances as Note pad file which we copied to excel for further processing of the values. A total of over 200,000 values for Received Power at different distances were attained.

Using the Received Power, power density at each of the different locations was obtained using unity gain for the gain at the Receiver
This is from Friss'equation as shown below;

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi d)^2} \tag{3.1}$$

$$\frac{P_T G_T}{4\pi d^2} = \frac{4f^2 \pi P_R}{c^2 G_R} \tag{3.2}$$

$$PowerDensity = \frac{4f^2 \pi P_R}{c^2 G_R} \tag{3.3}$$

Where P_T is a transmit power, G_T is a transmit antenna gain and d is a Base Station to User Equipment distance in meters, P_R is the Received Power, G_R is the Gain of the Receiver, f is the frequency and c is the velocity of the electromagnetic radiation.

Using the Power Density, we went ahead to compute the Specific Absorption Rate at each of the different distances from;

$$SAR = \frac{2PD(1 - R^2)}{\delta\rho} \tag{3.4}$$

Where R is the reflection coefficient, δ is the skin penetration in metres and ρ is the density of the human body ($1g/cm^3$ was used)

For 28 GHz the operational frequency for 5G UMa and UMi , the skin penetration is 1mm and refection coefficient of 0.6[4].

3.2 Measuring Power Density and Specific Absorption Rate for 4G Cellular Systems

Initially, physical measurements from different base stations were to be done, however, due to the COVID-19 lock down, this was not done.
Instead, a 4G Cellular network of 4G UMa was modelled and simulated using NYUSIM as it could easily give Received Power values on in put of the desired 4G parameters.

3.2.1 Modelling and Simulating 4G UMa

Just as in the case of 5G, the following network specifications were input in NYUSIM and the simulation done;
The 4G specifications are as shown in Table 3.3

	Parameter	**Value**
Channel Parameters	Operating Frequency	2 GHz
	RF Band width	20 MHz
	Transmitter Power	46 dBm
	Base Station Separation	500m
	AP Height	25m
	UE Height	1.5m
	Environment	Line Of Sight
	Transmission Type	FDD
Antenna Parameters	Number of Transmitter Antenna Elements	2
	Number of Receiver Antenna Elements	2
	Transmitter Antenna Spacing	0.5 wavelength
	Receiver Antenna Spacing	0.5 wavelength

Table 3.3: 4G UMa parameters

Power Density Values and Specific Absorption Rate values were obtained like in the 5G case.
For 2 GHz the operational frequency for 4G UMa, the skin penetration is 6mm and reflection coefficient of 0.8
.

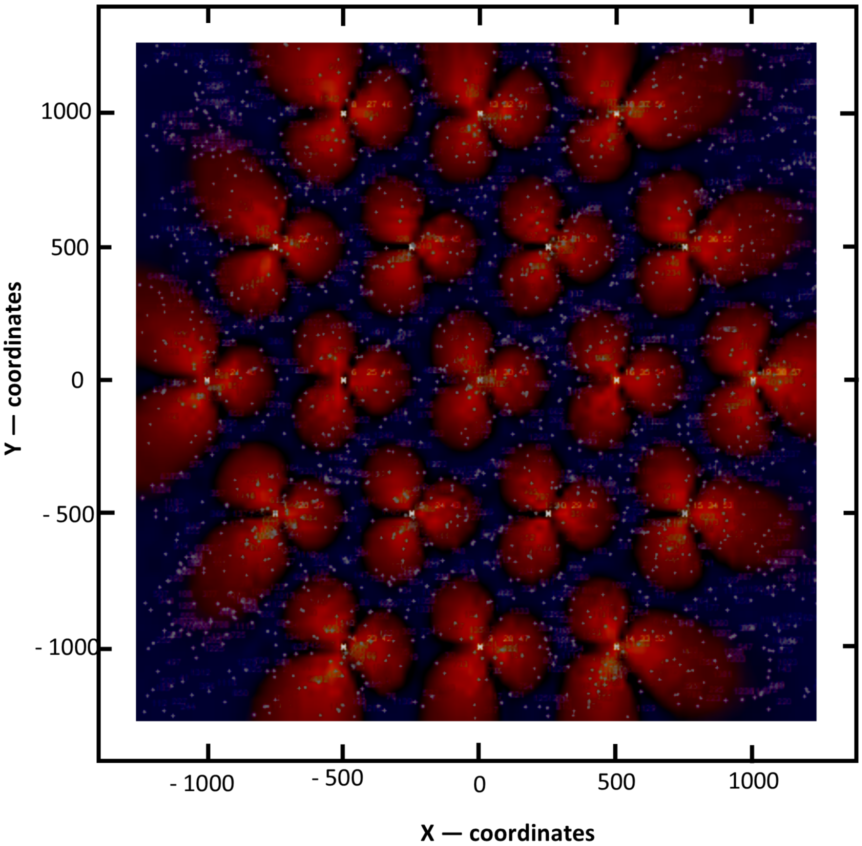

Figure 3.3: 4G UMa Base Station Setup

Considerations are that the network is fully loaded and operational.

3.3 Chapter Summary

The modeling and simulations of the 5G UMi, 5G UMi , 5G Indoor and 4G networks are described in this chapter. Computations of the values of PD and SAR from the Received Power values are also described.

Chapter 4
Results

This Chapter shows the Results obtained for PD and SAR after computation. The results are represented graphically. The results are discussed and mitigation protocols for Specific Absorption Rate proposed.

4.1 Out door Scenarios

4.1.1 Power Density Results from the different deployment scenarios

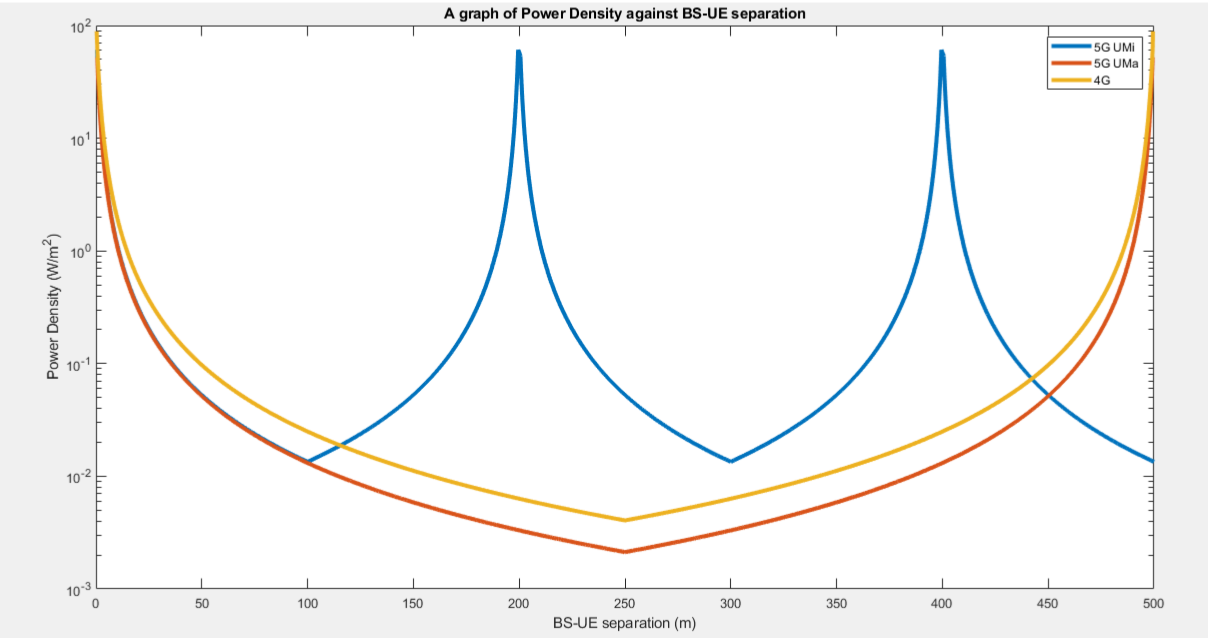

Figure 4.1: A plot of Power Density against BS-UE separation

From Figure 4.1 ,it is noted that PD values greatly reduce with increase in distance and hence necessitating the use of a logarithmic scale on the vertical.

Starting with 5G UMi, the Power Density reduces rapidly due to a high signal attenuation at 28 GHz. A reduction from over 60 W/m^2 is to less than 10 W/m^2 is noted within a distance of 5m. The reduction increases rapidly as the BS-UE separation increases to a value as low as 0.01 W/m^2 at 100m. However, after 100m, the Power Density is noted to increase in a similar manner in the opposite sense as the reduction. This is as a result of handover of the UE to another BS. On handover, the BS-UE separation starts reducing instead as the UE is getting closer to the next BS and therefore an increase in the PD.

Since the BS are 200m apart, each of them cover a radius of 100m in their cells. Therefore, after every 100m, the UE is handed over to the next BS and hence the continuous decrease and increase of PD throughout the 5G UMi network at 100m intervals.

There is a chance of exposure to high PD values in the 5G UMi network due to the close proximity of the base stations. From Figure 4.1, it can be noted that PD values are generally higher in terms their cumulative distribution when compared to the 5G UMa and 4G UMa

.

For 5G UMa, there is a rapid attenuation exactly similar to that of 5G UMa for the first 100m. The reduction reduces rapidly to as low as 0.002W/m^2 at 250m. After 250m, an increase is noted. This results from the UE being handed over to the next BS.. This happens since the cells for the 5G UMa network are 500m apart with the base stations covering a radius of 250m.

A 5G UMa network compared to a 5G UMi network yields a lower chance of exposure to high values of PD since the base stations are more apart. It is also noted that PD values from 5G UMa are generally lower those from 4G UMa all throughout a similar network.

For the 4G network the PD values, are higher than those of 5G UMi and 5G UMa for a BS-UE separation of 0-100m. This is a result of lower attenuation at 2GHz for the 4G when compared to the 28 GHz of 5G. Also the transmit Power of 4G being higher (44 dBm) when compared to that of 5G (35dBm) results into higher received Power values and in turn higher PD values.

The PD values through a network of 4G are higher in comparison to those of 5G UMa reducing from over 80 W/m^2 to close to 0.004 W/m^2 at 250m. After 250 m, the UE is handed over to the next BS and hence the increase in the PD.

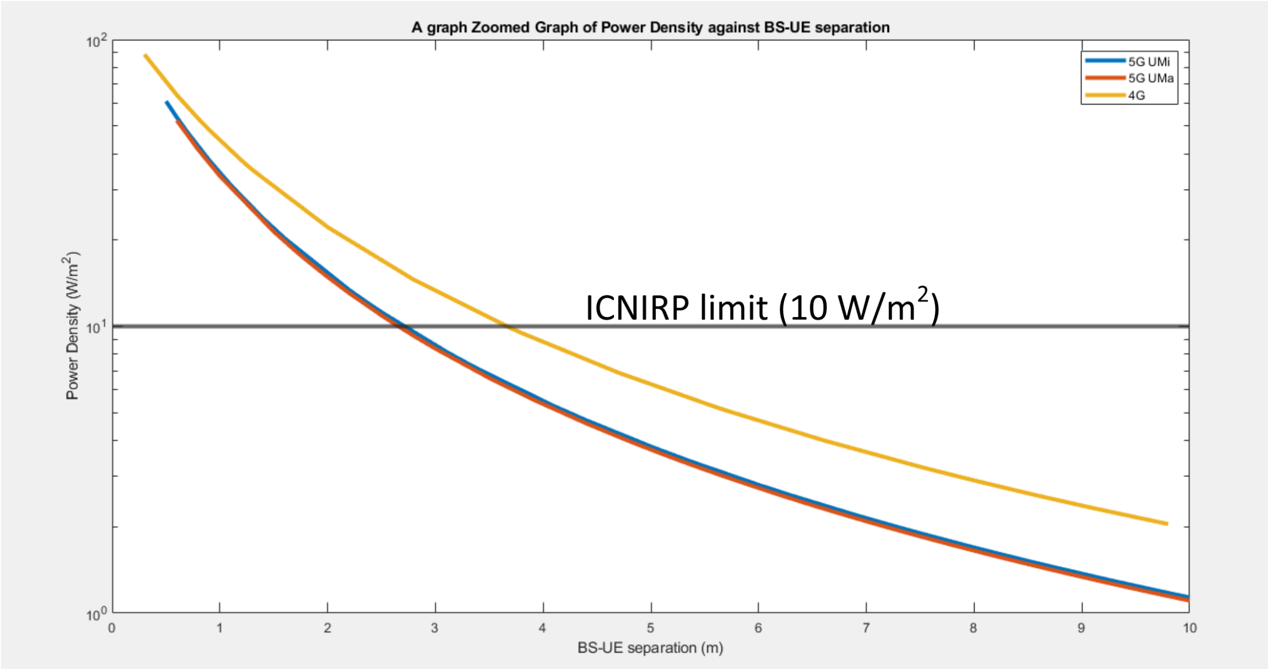

Figure 4.2: A zoomed plot of Power Density against BS-UE separation

In Figure 4.2, the graph is zoomed in .It is noted that both 5G UMi and 5G UMi cross the ICNIRP limit for a BS-UE separation of 3m. For the case of 4G, the ICNIRP limit is crossed at about 4m.

PD values from 5G go to as high as 60 W/m^2 closest to the BS while those of 4G reach as high as $80W/m^2$

From Figure 4.1 and 4.2 , it can be noted that in terms of Power Density the ICNIRP limit is exceeded for only small distances and the PD values for 5G are below the limits for the larger part of the network.

In terms of PD, since the exposure values of PD are close to those of 4G, it can be concluded that its safety in terms of PD is similar to that of 4G especially for the case of 5G UMa.

4.1.2 Specific Absorption Rate Results from the Deployment Scenarios

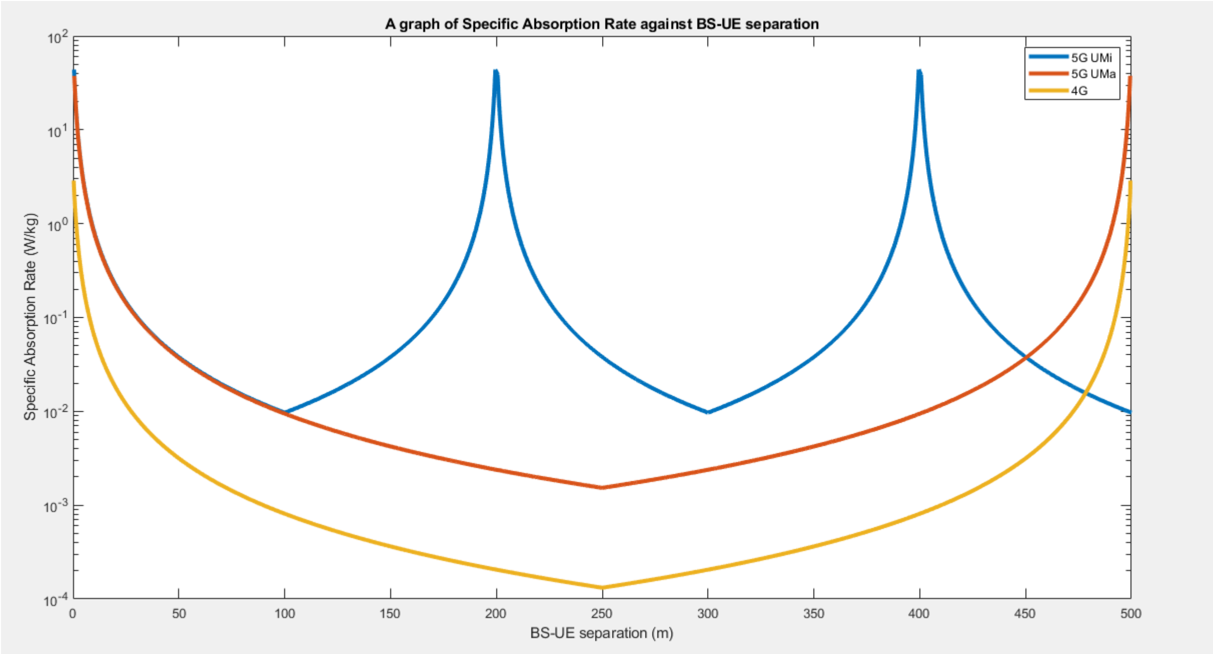

Figure 4.3: A plot of Specific Absorption Rate against BS-UE separation

In Figure 4.3, the SAR values were computed from the PD values using Equation 3.4 Starting with 5G UMi, SAR values rapidly reduce from over 30 W/kg to as low as 0.01 W/kg after 100m BS-UE separation. Due to handover of the UE to the next BS, the SAR value starts increasing. In comparison with 4G, the 5G UMa SAR values of 5G UMi are higher generally.

Also due to close separation of the base stations that is 200m, there is a higher chance of exposure to high SAR values when compared to both 5G UMa and 4G.

Taking the case of 5G UMa, SAR reduces rapidly from as much as 30 W/kg to as low as 0.001 W/kg at 250m. After 250m, when the UE has been handed over to the next BS, the SAR starts increasing

The SAR values are generally way higher than those from 4G for similar distances. This shows that in terms of SAR, 5G exposes a user to higher SAR values in comparison to the existing 4G systems.

For the case of 4G,the SAR values reduce from 2W/kg for a close BS-UE separation to as low as 0.0001W/kg for a separation of 250m. After this separation, handover occurs and an increase occurs. The SAR values from 4G are way smaller than those from 5G.

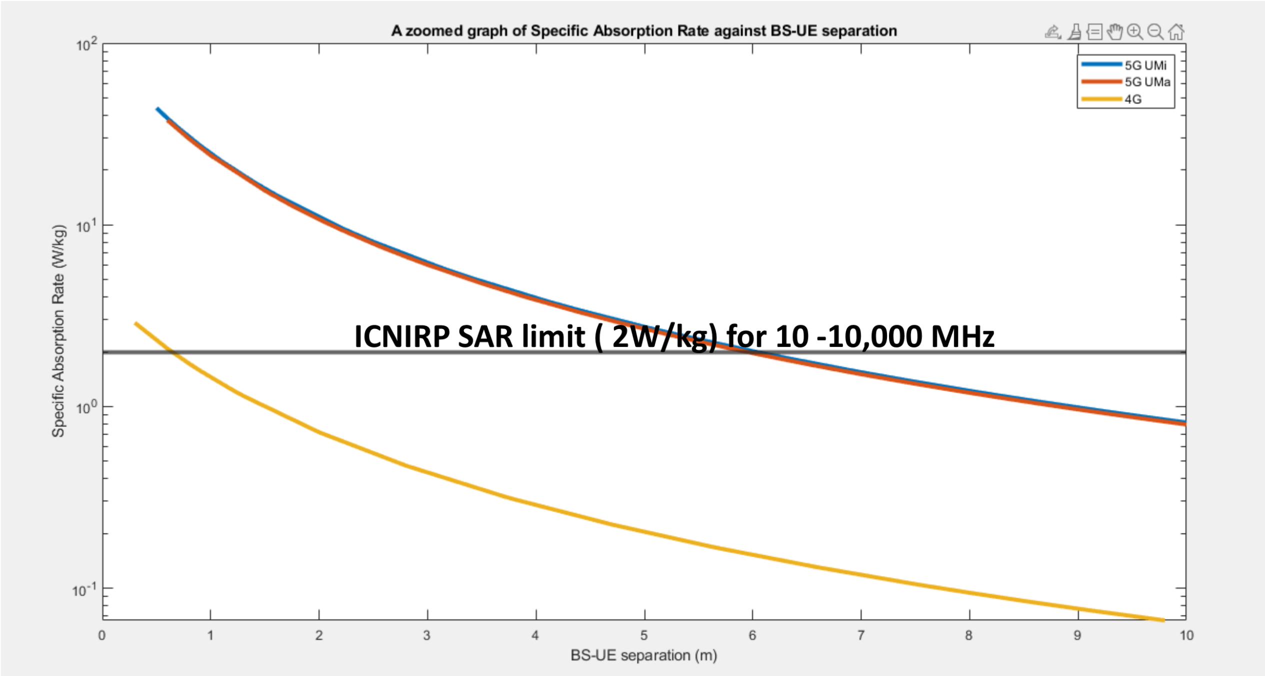

Figure 4.4: A zoomed plot of Specific Absorption Rate against BS-UE separation

In Figure 4.4, the graph from Figure 4.3 is zoomed

Unfortunately, the ICNIRP guidelines provide a SAR limit for only a near field with more concentration on the uplinks and this is 2W/kg for a frequency range of 10-10,000 MHz. For the higher frequencies for example 28 GHz for the case of 5G, no limits are set.

From Figure 4.4, for 5G UMa and 5G UMi, when the limit of 2W/kg, it is noted that the limit is exceeded at 6m BS-UE separation and the SAR value goes to a high as 30W/kg for a close BS-UE separation. For the case of 4G, this limit is only exceeded narrowly at 1m reaching close to 2.5 W/kg for a close BS-UE separation.

Our findings show that SAR values in the 5G scenarios are quite higher than those of 4G and earlier technologies (3G and 2G) and the limit of 2W/kg (for 10-10,000 MHz) is actually exceeded for a close BS-UE separation.

4.2 Indoor Scenario

4.2.1 Results from the 5G Indoor Scenario

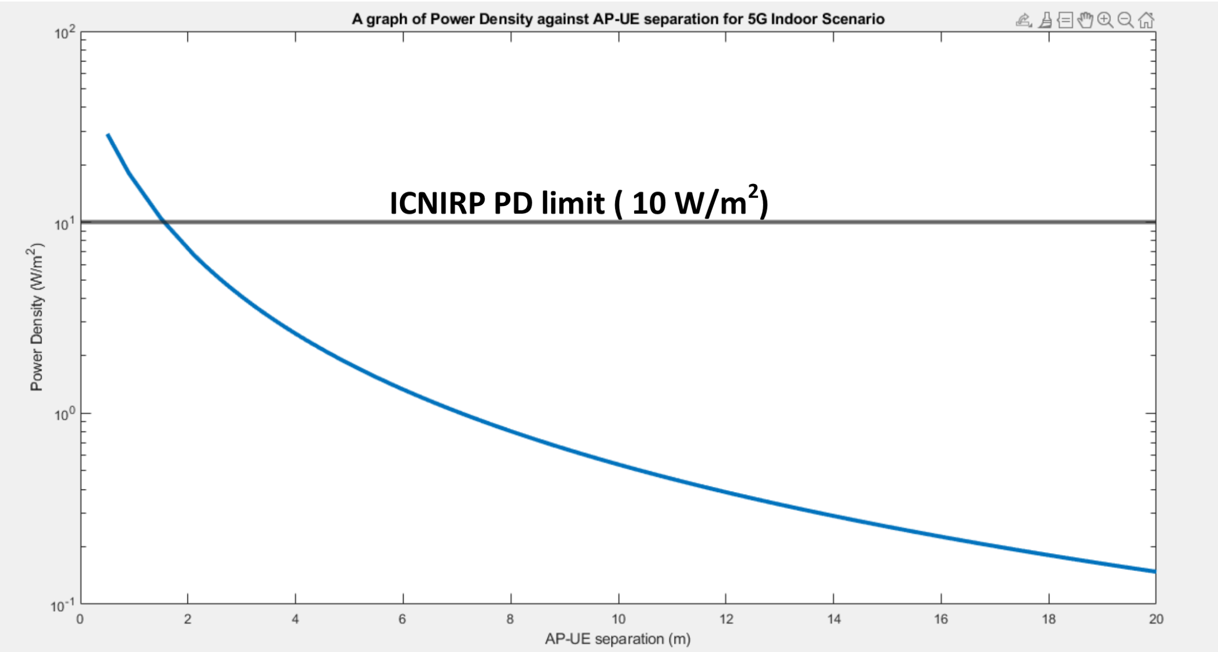

Figure 4.5: A plot of Power Density against AP-UE separation for a 5G Indoor Setting with Line of Sight

From Figure 4.5, it can be noted that the PD values of 5G indoor reduce rapidly from as high as 30 W/m^2 to as low as $0.1W/m^2$ at an AP-UE separation of 20m.

The ICNIRP limit of $10W/m^2$ is exceeded at an AP-UE separation of 2m and below this limit for the rest of the separation distances.

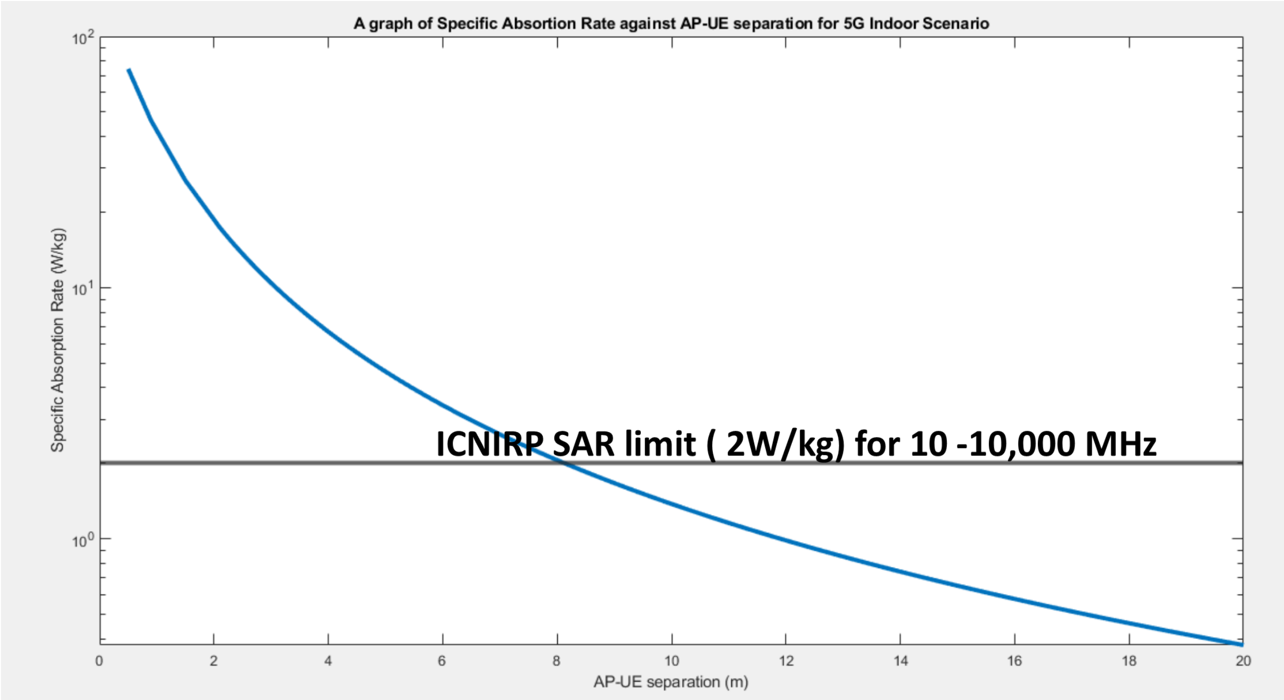

Figure 4.6: A plot of Specific Absorption Rate against AP-UE separation for a 5G Indoor Setting with Line of Sight

In Figure 4.6, it is noted that the SAR reduces from a high as 70 W/kg to a low as 0.4 W/kg at 20m. As compared to 5G of the outdoor, these values are higher.

Taking the limit of 2 W/kg (for 10-10,000 MHz) it is exceeded at 8m. SAR values are generally high for a longer part of the AP-UE separation in the indoor scenario.

One of the causes of a high SAR is a low skin penetration of approximately 0.5mm at 60 GHz[4].

4.3 Reasons why SAR is higher in 5G

SAR is higher in the case of 5G because of;

1. In a 5G downlink, the shallower penetration into human tissue yields a higher level of absorption at the surface of human skin. This is confirmed by the fact that an instantaneous SAR is inverse-proportional to the penetration depth . Penetration is about 1mm for 28GHz and 6mm for 4G at 2GHz.
2. Also, the small-cell topology adopted in 5G to overcome the higher attenuation at high operating frequencies yields a smaller BS-UE distance. Also, larger phased array antennas contribute to the increase of PD in which in turn results in higher SARs.

4.4 Recommendations for safety as regards the high SAR values

Although there is no guideline set in terms of SAR above 10,000MHz, SAR is a more informative metric than PD. The results obtained show that there is need for regulations for downlinks in terms of SAR at higher frequencies such as 28 GHz for outdoor and 60GHz for indoor.

However, since no limits are in place yet, we propose/recommend two mitigation models, one for indoor and the other for outdoor. The aim of these is to reduce on the EMF exposure in terms of SAR.

4.4.1 Proposed mitigation protocol for Specific Absorption rate for the case of the 5G indoor scenario

In the indoor scenario, exposure levels in terms of PD and SAR exceeded those of current Wi-Fi This is due to operation at a high frequency of 60 GHz, For a close AP- UE separation (less than 2m), the PD actually exceeded the ICNIRP limit 10 W/m^2. Also, the SAR exceeded the limit set for the near field which is 2 W/kg (This is for the frequency range of 10-10,000MHz).

The SAR values are generally high. This would imply higher EMF absorption into the human skin. Below is a proposed protocol to mitigate EMF exposure in the indoor scenario in terms of SAR putting the ICNIRP limit under consideration.

Since data traffic keeps varying, the protocol proposed entails monitoring the traffic and usage and in turn increase/decrease the transmit power. Transmit power affects data rate, however, especially in cases with low traffic, a slight reduction in the transmit power would still avail a data rate that guarantees a Quality of Service for 5G.

Traffic increases with an increase in the number of users or as a result of the internet services being accessed by a certain user. For example, heavy downloads, video streaming, and video calls result in higher traffic. In this model, we concentrate on the number of users as a mode that results in a traffic increase.

A proposal transmit power reduction from 24 dBm to a range between 16 dBm to 20 dBm. This would help lower the PD and in turn lower the SAR despite operation at 60 GHz frequency. Since the AP is set to cover up to a distance of about 20m, the above range of transmit powers can provide sufficient signal strength. The AP transmit power is adjusted according to the number of users according to set requirements or program as shown in Table 4.1 that could be installed on a processor at the AP.

With this protocol, the target is reduced exposure to high SAR values in the indoor environment.

In the next step, PD received at each of the UEs connected is monitored so that its value does not exceed a set PD that would yield a SAR greater than 2W/kg. If it is found to

Number of Users	Transmit Power
0-5	16 dBm
6-10	17 dBm
11-15	18 dBm
16-20	19 dBm
>20	20 dBm

Table 4.1: Proposed Trasmit Powers for different number of users

be below the set PD, the operation is continued with this transmit Power. However, if it is found to exceed, the transmit power is reduced by 1dBm.

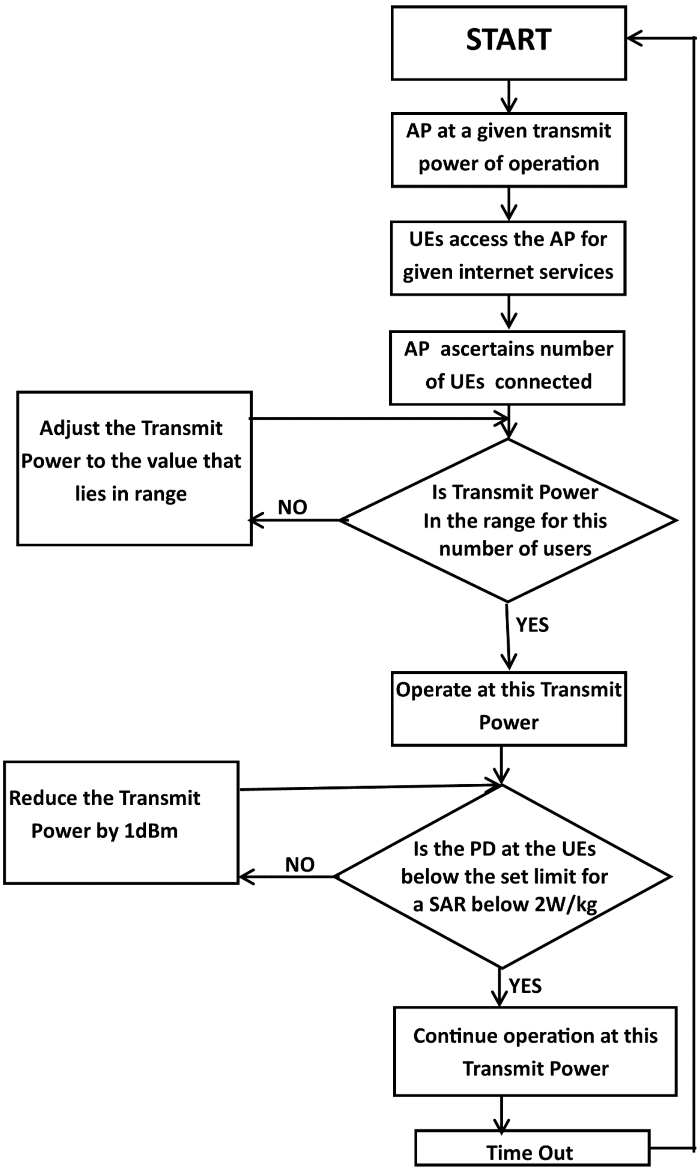

Figure 4.7: Flow Chart to of the Proposed Indoor Protocol

In this model there are two achievements;

1. Exposure to high level SAR is minimized especially in cases of minimal users where

the data traffic is low.

2. Exposure beyond the limits set by ICNIRP is prevented as per terms of SAR.

4.4.2 Proposed Mitigation of Specific Absorption for the 5G Outdoor Scenarios

For outdoor, even though the SAR values exceed the limit for a close AP-UE distance, the SAR values are generally high hence a higher EMF absorption into the human body. For the above reasons, we proposed a protocol to mitigate EMF exposure effects due to high SAR. The protocol aims at shielding the SAR.

Electromagnetic shielding is used to confine electromagnetic energy within the bounds of a specific region and to prevent the propagation of such energy into a designated area

In this protocol, the aim is to reduce SAR values using a ferrite shield.

A ferrite sheet is introduced between the UE antenna and the external UE cover, in order to reduce exposure to the skin/body/head close to the UE. This is because ferrite materials have very low conductivity which leads to smaller induced currents when exposed to EM waves and they cancel the magnetic field part of an incident EM wave

The size of the ferrite plate is identical to the area of the handset box.

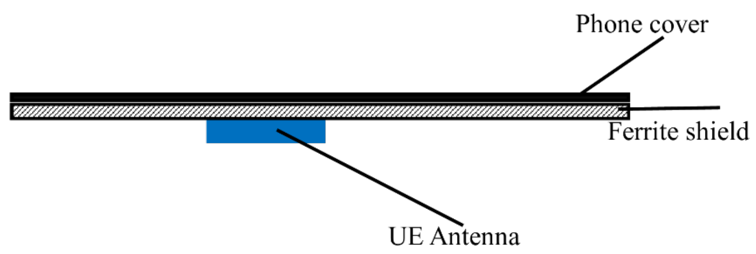

Figure 4.8: SAR shield placed between the antenna and device cover

To ensure safety with minimal effect on data rates, our proposal entails using a sensor assembly for detecting received Power and quantifying it to a given value of PD from the and a mechanical system that adjusts the ferrite shield by rolling it

The model involves a ferrite sheet that includes a plurality of ferrite cells partially movable relative to one another to provide flexibility

The operation is as follows;

1. A threshold value of PD for which the SAR of 2W/kg is exceeded is set.

2. When the sensor detects that this PD is exceeded shield is rolled out to cover the antenna and rolled back in cases when the PD is below the threshold.

It is expected that a SAR reduction of 47.68% over 1 gram of tissue will be realized.

From the above it is illustrated that shielding the UE to reduce SAR can effectively keep the human EMF exposure level under the safety margin.

Although our target is to lower EMF exposure, the presence of the ferrite sheet results in a reduction in the Received Power and hence affecting the downlink data rate to some extent

4.4.3 Extent to which the proposed protocols minimize the Specific Absorption Rate

The mitigation yields the distribution in Figure 4.9,

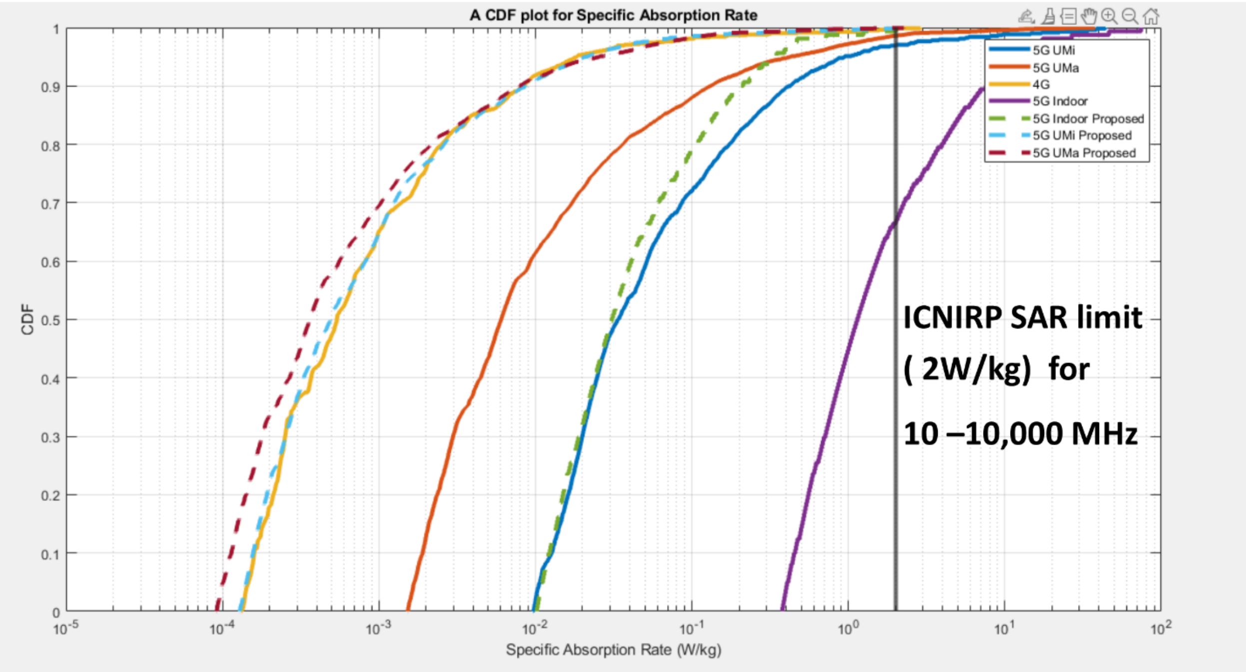

Figure 4.9: CDF plot of the distributions of SAR from different deployment scenarios

With the mitigation, 2W/kg is set as the threshold and it noted that in the proposed protocol, the SARs do not exceed the limit. However, the SAR exposure is still higher in the proposed indoor model due to operation at a high frequency of 60 GHz and a low skin penetration of approximately 0.5mm

4.4.4 Effect of the Mitigation on the data rates

Because the mitigation results into a reduction of the received Power, the data rates are affected.These are calculated from Equation 2.7 The findings are as shown in Figure 4.10;

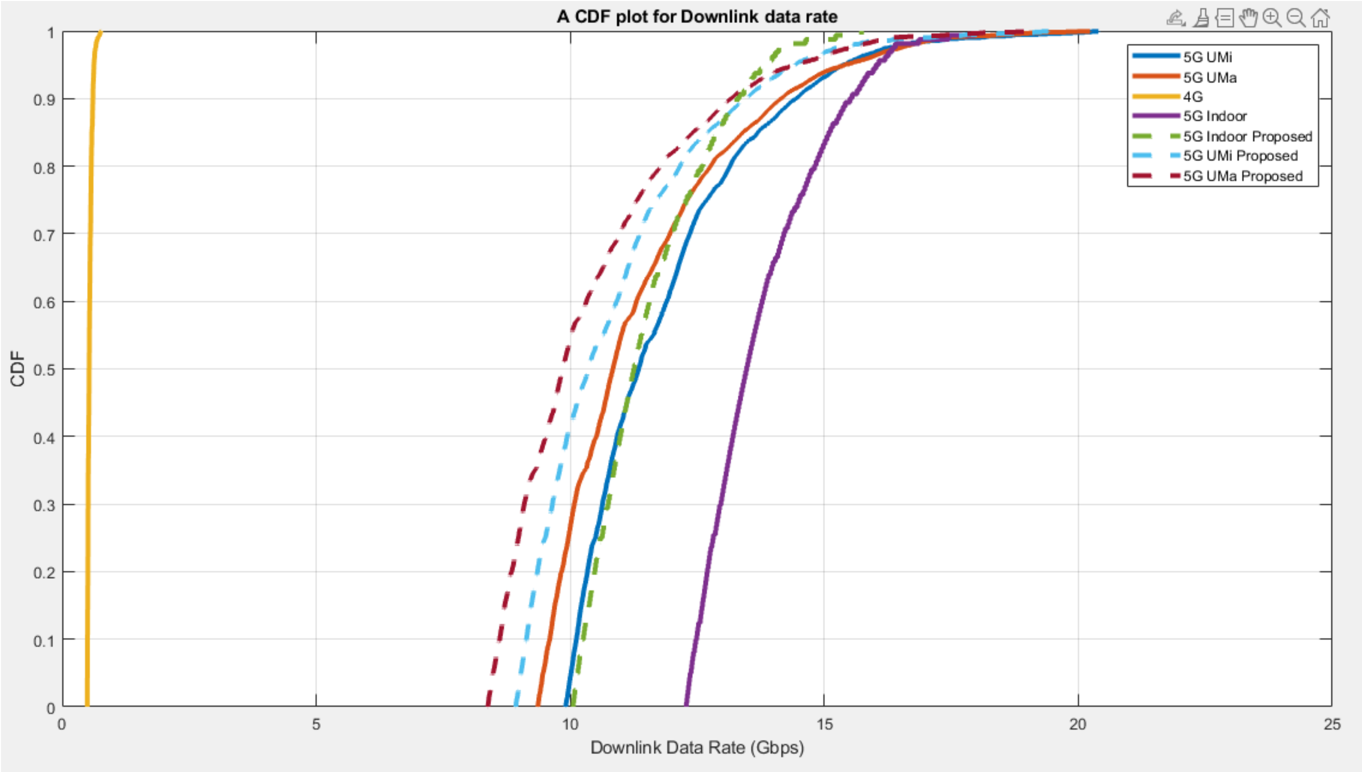

Figure 4.10: CDF plot of the data rates from different deployment scenarios

It is noted that though the mitigation results into a reduction in the data rates, however, the data rates for the two proposed mitigation schemes can still yield desired results for a good quality of service from 5G

4.5 Chapter Summary

In this Chapter Results in terms of PD and SAR are obtained for 5G UMi, 5G UMa, 5G Indoor,and 4G . Since SAR was found to be high, mitigation protocols are proposed. The SAR outcome after mitigation is also obtained and the effect of the mitigation on data rates found.

Chapter 5

Conclusion, Recommendations and Further Work

5.1 Conclusion

This report shows an evaluation of EMF from downlinks for different 5G deployment scenarios. Outdoor scenarios (5G UMa and 5G UMi) and an indoor scenario were modelled and simulated successfully and were used as a basis of the investigation. A 4G network was modelled and simulated as well.

Using the Average received Power at different UE locations for each of the scenarios, Power density and Specific Absorption Rate values were obtained at each of the locations.
It was found that EMF exposure levels in terms of Power density were relatively similar to those of 4G with a larger section of the network below the regulatory limit of 10 W/m^2 by ICNIRP with the limit being exceeded for a close BS-UE separation.

However, in terms of Specific Absorption Rate, exposure levels were much higher than those from 4G from both the indoor and outdoor scenarios and this prompted us to propose mitigation protocols for SAR and analyzed how the mitigation would affect the networks' performance in terms of data rates. It was found that the mitigation would lower the data rates but they remained in the expected range of values for 5G.

5.2 Recommendations

There is a need for setting up regulations for downlinks in terms of Specific Absorption Rate for high frequencies as it is found to be higher than that from earlier technologies. Currently there is no guideline set in terms of SAR above 10 GHz yet SAR is a more informative metric.

Emphasis should be put on mitigation of EMF Exposure from 5G with emphasis on Specific Absorption Rate.

5.3 Further work

Simulating and modeling 5G networks that follow the proposed mitigation protocols and investigating their performance and EMF exposure levels.

Taking actual measurements of Received power after actual deployment of 5G networks in Uganda and ascertaining the Power Densities and Specific Absorption Rates.

Bibliography

[1] E. V. P. M. K. B. A. G. C. D. Seungmo Kim, Coexistence of 5G with the Incumbents in the 28 and 70 GHz bands, Globecom Workshops: IEEE, 2017.

[2] Z. Khan, Millimeter-wave mobile broadband with large scale spartial processing for 5G mobile Communications, Allerton: 50th Annual Conference Communication Control, 2012.

[3] I. N. a. S. Kim, Adverse impacts of 5G downlinks on human body, South East Carlifornia: IEEE, 2019.

[4] T. S. R. a. C. M. C. T. Wu, Safe for generations to come: Considerations of safety for millimeter waves in wireless communications, IEEE Microwave Magazine, 2015.

[5] . R. a. N. S. M. Agiwal, "Next generation 5G wireless networks: A comprehensive survey," IEEE Communications Surveys Tutorials, vol. 18, no. 3, pp. 1617-1655, 2016.

[6] S. S. R. M. H. Z. Y. A. K. W. G. W. J. S. M. S. a. F. G. T. Rappaport, "Millimeter-wave mobile communications for 5G cellular: It will work," IEEE Access, vol. 1, no. 1, pp. 335-349, 2013.

[7] FDA, "Scientific Evidence for Cell Phone safety," FDA, 02 10 2020. [Online]. Available: www.fda.gov/radiation-emitting-products/cell-phones/scientific-evidence-cell-phone-safety. [Accessed 2021].

[8] P. J. S. M. D. A. M. S. . I. A. Gupta. A, "Computational intelligence-based intrusion detection systems for wireless communication and pervasive computing networks," in IEEE International Conference on Computational Research, India, 2013.

[9] J. N. M. a. F. G. T. S. Rappaport, "State of the art in 60 GHz integrated circuits systems for wireless communications," Proc IEEE, vol. 99, no. 8, pp. 1390-1436, August 2011.

[10] C. L. Tang, Fundamentals of Quantum Mechanics: For Solid State Electronics and Optics, Cambridge UK: Cambridge University Press, 2005.

[11] F. C. Commission, "Guidelines for Evaluating the Environmental Effects of Radio frequency Radiation," Washington DCC, 1996.

[12] R. D. L. P. DJ Brenner, "Cancer risks attributable to low doses of ionizing radiation," Assessing what we really know, vol. 100, no. 24, pp. 13761-13766, November 2003.

[13] U. C. Commission, "National Survey on Electromagnetics(EMF) exposure around GSM Base Stations in Uganda," in Uganda Communications Commission, Kampala Uganda, 2015.

[14] J. O. d. L. a. C. S. Ezell, "Observing-responses of rats exposed to 1.28 GHz to 5.62 GHz microwaves," Bioelectromagnetics, vol. 1, no. 2, pp. 183-198, 1980.

[15] J. O. d. Lorge, "Operant behavior and colonic temperature of Macaca mulatta exposed to radio frequency fields at and above resonant frequencies," Bioelectromagnetics, vol. 5, no. 2, pp. 233-246, 1984.

[16] "IEEE Standards for Safety Levels with Respect to Human Exposure to the Radio Frequency Electromagnetic Fields," IEEE Standard, 2005.

[17] J. C. Lin, "Safety standards for human exposure to radio frequency radiation amd their biological rationale," IEEE Microwave Magazine, vol. 4, no. 4, pp. 22-26, December 2003.

[18] D. P. B. L. E. L. T. M. O. E. T. F. Rusek, "Scaling up MIMO: Opportunities and challenges with very large arrays," IEEE Signal Process Magazine, vol. 30, no. 1, pp. 40-60, January 2013.

[19] I. C. o. N.-I. R. Protection, "ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to300 GHz)," in Health Physics, vol. 74, 1998, pp. 494-522.

[20] F. C. Commission, "Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields," Washington DC, 2001.

[21] D. L. a. B. H. M. Castellano, "Hybrid precoding for millimeter wave systems with a constraint on user electromagnetic radiation exposure," in Asilomar Conference on Signals, Systems and Computers, 2016.

[22] A. R. a. N. S. M. Agiwal, "Next generation 5G wireless networks: A comprehensive Survey," IEEE Communications Surveys Tutorials, vol. 18, no. 3, pp. 1617-1655, 2016.

[23] F. C. Commission, "Radio Frequency Radiation Exposure Limits," in in Code of Federal, Washington DC, 2017.

[24] A. Ahlbom, "Guidelines for limiting exposure to time-varying electric fields," in Health Physics, 1998, pp. 494-521.

[25] E. Kelley, "EMFsceintist.org- International Scientists Appeal to U.N to Protect Humans from Electromagnetic Fields and Wireless Technology,"EMFscientist.org, 2021. [Online].

[26] T. Rappaport, and C. Collins, The human body and millimeter-wave wireless communication systems: interactions and implications, in Proc. IEEE International Conference on Communications (ICC) (2015).

[27] Nasim, Imtiaz, "Analysis of Human EMF Exposure in 5G Cellular Systems" (2019).

[28] New York University and NYU WIREL,"NYUSIM User Manual"April 2017