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Analysis of Human EMF Exposure in 5G Cellular Systems

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ANALYSIS OF HUMAN EMF EXPOSURE IN 5G CELLULAR SYSTEMS

by

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(Under the Direction of Seungmo Kim)

ABSTRACT

Increasing concerns of communications at a frequency spectrum higher than 6 GHz have gained international alarm that suggests more research is needed before it is deployed successfully. In this context, in the first part of this thesis, we investigated the human electromagnetic field (EMF) exposure in indoor and outdoor environments from fifth-generation (5G) downlink communications and compared its impacts with the present cellular technologies considering the features that the 5G will likely adopt. The second part focuses on mitigation of human exposure for both indoor and outdoor environments with two different methods adopted. Our simulation results suggest that while the impacts from 5G communications cross the regulatory borders for a very short separation distance between base stations (BSs) and user equipment (UE), the exposure level remains high throughout the network compared to the present systems. This work also highlights the significance of considering SAR for the measurement of exposure compliance in downlinks.

INDEX WORDS: Downlink, Above 6 GHz, Human EMF exposure, PD, SAR, Separtaion distance, Outdoor, Indoor

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DEDICATION

This thesis is dedicated to my beloved parents, my only sister and my beloved wife.

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CHAPTER 1

INTRODUCTION

This chapter briefly reviews the requirements of the fifth-generation wireless systems (5G) and the threat that this future cellular technology is going to impose along with its advantages. The organization of this thesis is outlined at the end of this chapter.

1.1 5G and its Requirements

It has been more than a few decades since the mobile wireless communications were initiated with the first generation, voice-only systems. Over the last couple of decades, the world has witnessed gradual but steady evolution of mobile wireless communications towards the second, third and fourth generation of wireless networks. With the ever increasing popularity of smart devices, currently all- IP based fourth-generation long-term evolution (LTE) networks have become a part of our everyday life. As such, a set of new and user-oriented mobile multimedia applications, such as mobile video conferencing, streaming video, e-healthcare, and online gaming are gaining more popularity in the market. These new applications are not only satisfying users' requirements, but also opening up new business horizons for wireless operators to increase their revenue [1].

Almost all wireless communications use the spectrum within 300 MHz to 3 GHz band, often termed as "sweet spot" or "beachfront spectrum" [1]. The expectation from sub millimeter-wave (mmW) band to accommodate the exploding mobile traffic and connectivity seems to be a big challenge. Thus, for increasing capacity the wireless communications cannot help, facing the new challenges of high frequency bandwidth. The key essence of next generation 5G wireless networks lies in exploring this unused, high frequency band, ranging from 3-300 GHz. Thus, the availability of a big chunk of high frequency spectrum is opening up a new horizon for spectrum constrained future wireless communications [2]. Fig. 1.1 illustrates a probable bandwidth availability for 5G.

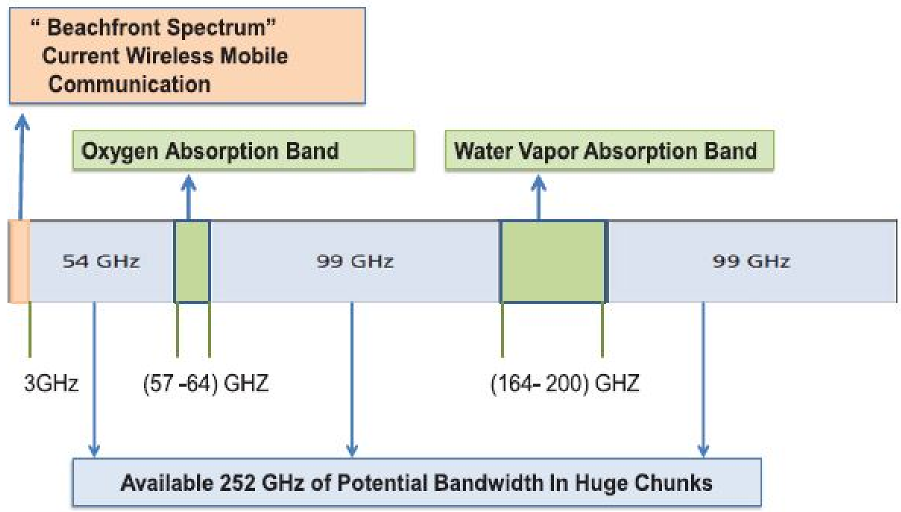

Figure 1.1: Spectrum availability for 5G from 3 to 300 GHz [1]

Some of the major requirements of the next generation 5G technology can be identified as [3]-[5] :

- A data rate up to 10 Gbps or more in real network’s which is almost 10 times the increase from traditional LTE networks theoretical peak data rate of 150 Mbps.
- 1 ms round trip latency that is almost 10 times the reduction from 4G’s 10 ms round trip time.
- High bandwidth in the unit area which is needed to enable the large number of connected devices with higher bandwidths for longer durations in a specific area.
- Enormous number of connected devices in order to realize the vision of IoT, the emerging 5G networks need to provide connectivity to thousands of devices.
- Perceived availability of 99.999 percent: 5G envisions that the network should practically be always available.
- Almost 100 percent coverage for ‘anytime anywhere’ connectivity: 5G wireless networks need to ensure complete coverage irrespective of users’ locations.

- Reduction in energy usage by almost 90 percent: Development of green technology is already being considered by standard bodies. This is going to be even more crucial with high data rates and massive connectivity of 5G wireless.

- High battery life: Reduction in power consumption by devices are fundamentally important in emerging 5G networks.

These requirements, especially the increasing demand for higher data rates and uninterrupted reliable service have made the frequency spectrum above 6 GHz a very promising candidate for future wireless communications because of its massive amount of raw bandwidth and extremely high data transfer capabilities. As a means to supply the latest skyrocketing bandwidth demand, the 5G mobile communications is expected to achieve far higher data rates compared to the previous-generation wireless systems [6]. It is almost in reality now; many network providers and device manufacturers are very close to bringing 5G to practice.

1.2 Possible Risk from 5G

Recently, however, a serious concern has been raised. It is acknowledged that exposure to electromagnetic fields (EMFs) has negative impacts on the human body. The 5G's requirement of a very high data rate necessitates a higher signal power at a receiver. For instance, a recent link budget study [7] indicates that for an increase of data rate from 1 to 6 Gbps, the required received power grows from -65 to -37.5 dBm. Such a higher signal power received at a user's end evokes concern on the increase in the amount of EMF energy imposed to the human user [8]-[10].

At frequencies above 6 GHz where forthcoming 5G mobile telecommunications system are likely to operate [14], two changes that will possibly occur have the potential to increase the concern of exposure to human users. First, *larger numbers of transmitters*

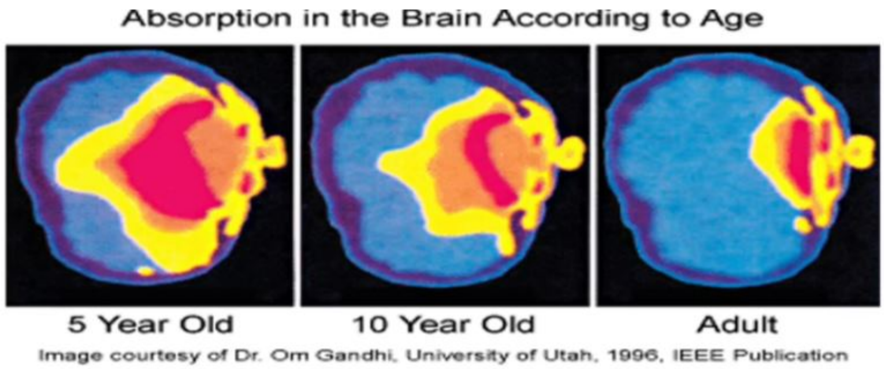

Figure 1.2: Exposure to EMF field effects in human brain [11]

will operate at the base stations (BSs) [1] [12]-[13] and mobile devices accordingly. Second, *narrower beams* will be used as a solution for the higher attenuation at high frequency bands [13]-[16]. Moreover, one important feature of the future cellular systems is small cell networks. The consequences of this change will be two-fold: (i) Access points (APs)/BSs will serve smaller geographic areas and thus are located closer to human users; (ii) larger numbers of APs/BSs will be deployed, which will lead to higher chances of human exposure to the EMFs generated by downlinks. These characteristics of the 5G systems have developed growing controversies among the researchers whether the technology poses a risk to human health [17].

But to the best of our knowledge, very few studies in the literature have claimed with certainty that EMFs generated by the 5G systems can impose a significant threat to human health [18]. However, the research is still in progress to find any gaps in knowledge for the safety of human health.

1.3 Thesis Organization

The organization of this thesis in terms of chapter and respective content will be as follows:

1. **Chapter 2:** Chapter 2 describes the background of human exposure to EMFs. The

amount of work done previously on this topic and the concerns are highlighted. The different existing guidelines measuring the human EMF exposure are also discussed.

2. **Chapter 3:** In this chapter, we present the system model of our work. The description of the systems we chose to analyze the human EMF exposure are stated in brief.

3. **Chapter 4:** This chapter deals with the analysis of the human EMF exposure case. The details of our work on which the results are simulated are illustrated in this chapter.

4. **Chapter 5:** We propose the network protocol for mitigation of human EMF exposure in this chapter. Mitigation of human EMF exposure for both outdoor and indoor environment are presented depending on the availability of resources. The proposed protocol for outdoor in this chapter is also published in the journal of Springer Annals of Telecommunication, 2019, titled as "Mitigation of Human EMF Exposure in Downlink of 5G".

5. **Chapter 6:** The numerical results of our work is presented in this chapter and the performance of our proposed protocol for both outdoor and indoor is provided. This chapter shows that our proposed model can effectively reduce the human EMF exposure in 5G cellular systems.

6. **Chapter 7:** We outlined the conclusion of this thesis in this chapter with some suggestions for possible future research.

CHAPTER 2

LITERATURE REVIEW

Human EMF exposure in wireless communications systems has been studied covering multiple aspects. We categorize the prior work and identify limitations in this chapter.

2.1 Measurement of Human EMF Exposure

Several organizations such as the United States (US) Federal Communications Commission (FCC) [19] and International Commission on Non-Ionizing Radiation Protection (ICNIRP) [20] set the maximum allowable limit on EMF radiation that can be allowed to penetrate into the human body. From the literature, this thesis report identifies three technical features adopted in 5G, which show potential to increase the concern of human EMF exposure 'further.'

First, the 5G targets to operate at *higher frequencies* (e.g., 28, 60, and 70 GHz [14]). The rationales are advantages such as (i) availability of far wider bandwidths than the current cellular standards, and (ii) possibility of integrating a larger number of miniaturized antennas in small dimensions, attributed to very small wavelengths [28]. Such a high-gain directional antenna array enables radiation energy to be focused in a certain direction, leading to an increased amount of EMF energy deposition in the main lobe pointing towards a human body [18].

Second, *larger numbers of transmitters* will operate. In 5G, more BSs will be deployed due to the employment of small cells [1] [12]. The consequences of this change are as follows: (i) BSs will serve smaller geographic areas and thus are located closer to human users, and hence (ii) chance of a human user being exposed to EMF gets higher.

Third, *narrower beams* will be employed in 5G as a solution for faster attenuation of a signal power due to the operation in high-frequency bands [28]. Very small wavelengths at such high frequencies can enable a radio frequency (RF) circuit to accommodate a massive number of antennas densely integrated. Such a multiple-antenna system is capable of generating a very large antenna gain. This higher concentration of electromagnetic energy again increases the potential for an EMF to more deeply penetrate into a human body. As such, a thorough review of the guidelines based on the previous communication's paradigm is being suggested in recent literature [21]-[23].

Possibilities of skin cancer due to EMF emissions at higher frequencies are reported previously [24]. Heating due to EMF exposure at a higher frequency such as millimeter wave (mmW) is absorbed within the first few millimeters (mm) within the skin; for instance, heat is absorbed within 0.41 mm for 42.25 GHz [17]. The normal temperature for the skin outer surface is typically around 30 to 35°C. The pain detection threshold temperature for human skin is approximately 43-45°C as reported [17] and any temperature over that limit can produce long-term injuries. Although agencies like the US Food and Drug Administration (FDA) and World Health Organization (WHO) believe that the weight of scientific evidence does not show an association for adverse health outcomes due to EMF fields [24], all these agencies have claimed that additional research is warranted to address any gaps in knowledge. In fact, WHO's International Agency for Research on Cancer (IARC) has classified EMF fields as possibly carcinogenic to humans [25].

The three major quantities used to measure the intensity and effect of EMF exposure are specific absorption rate (SAR), plane-wave equivalent power density (PD), and the steady-state or transient temperature [17][26]. However, selection of an appropriate metric evaluating the human EMF exposure still remains as an open problem. The FCC and ICNIRP consider PD as a metric for the measurement of safety at frequencies higher than 6 GHz [19] and 10 GHz [20], respectively, whereas 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 [27]. Also, regarding these guidelines, recent studies [18] [27] found that PD is not as useful as SAR or temperature

Table 2.1: The variations of exposure limits on PD to RF radiation in several countries [17].

Country/Guidelines	**PD Restrictions for General Public in W/m^2**	**Frequency Range (GHz)**
ICNIRP (1998)	10	2-300
FCC (1996)	10	1.5100
China (1987)	0.10	0.3-300
Russia (2003)	0.10	0.3-300
Switzerland (2000)	0.10	1.8-300
Italy (2003)	0.10	0.0001-300

Table 2.2: Comparison of the FCC and ICNIRP local SAR limits in the head and trunk for the general public. [17].

Exposure Standard	**SAR limit for RF Near field exposure (W/kg)**	**Frequency Range (MHz)**
ICNIRP	2	10-10000
FCC	1.6	0.1-6000

in the assessment of safety since PD does not display the level of EMF energy that is actually transmitted across the boundary or the amount of energy that is actually 'absorbed' in the body. The temperature may not be sufficiently accurate in the downlink as it can be dispersed over the air due to the long distance. Therefore, this paper examines the human EMF exposure by analyzing both PD and SAR.

The current existing guidelines adopted by different regulatory organizations of various countries on PD and SAR are presented in tables 2.1 and 2.2.

2.2 Reduction of Human EMF Exposure

As the impact of radiation from 5G cannot be ignored, there remains a strong necessity for the development of EMF mitigation schemes for the successful deployment of 5G systems.

Most of the prior studies that showed concerns about the human EMF exposure [17]-

[18][31] focused only on uplinks for frequencies above 6 GHz, due to shallow penetration depth at such high frequencies. Propagation characteristics at different mmW bands and their thermal effects were investigated [27]. Emission reduction scheme and models for SAR exposure constraints are studied in recent works [29]-[30].

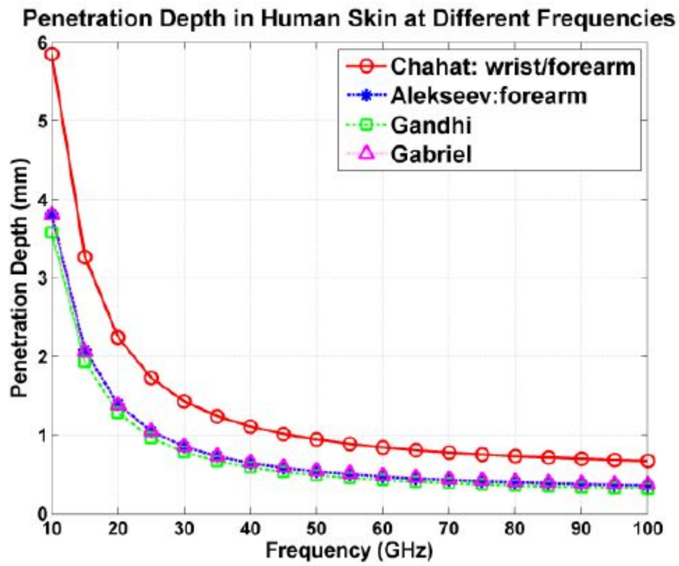

Figure 2.1: The penetration depth in the human skin with the increase of exposure frequencies using different skin models [27]

2.3 Contributions

The contributions of this thesis can be highlighted as follows:

1. While previous studies focused on uplinks only, this paper analyzes the human EMF exposure in *downlinks*. In order to fulfill the requirement for higher data rates in 5G downlinks, the received signal power is expected to be accordingly higher compared to the previous generations of wireless systems. This will lead to more severe and frequent occasions where human users are exposed to higher levels of EMF energy upon reception.

2. It explicitly *compares the human EMF exposure in downlinks* of 5G based on the 3rd Generation Partnership Project (3GPP) Release 15 [32] to those of the legacy standards–i.e., Release 9 [33] (representing the 3.9G technology) and Release 12 [34] (representing the 4G technology as one of the latest Releases by 3GPP as the concurrent systems) for outdoor. This paper calculates PD and SAR of all aforementioned systems to provide a clear understanding of the exposure level on the technical evolution to 5G.

3. We highlight the merits of considering *SAR* in the evaluation of human EMF exposure even at higher frequencies–i.e., above 6 GHz. SAR has been regarded as less effective at such high frequencies (e.g., mmW) since the range of EMF energy absorption into human tissues is shallower compared to lower frequencies. However, SAR is a more effective metric than PD to present the actual influence of human exposure to EMF. Our results show that EMFs generated in downlinks can also cause higher SAR at 28 GHz. This implies that in spite of such shallow penetration into a human body, the level of EMF energy deposition on the human skin surface is far higher, which can potentially threaten human health.

4. This research also provides a comparison of human EMF exposure at indoors between the 5G at 60 GHz band and existing Wi-Fi (or WiFi) based on IEEE 802.11n specifications at 5 GHz band to represent how the technical evolution to 5G can impose threats in the indoor network.

5. As a remedy for the potential threat to human health, this paper *proposes downlink protocols for both outdoor and indoor* in order to mitigate the human EMF exposure at higher frequencies. It elects the serving AP for a UE among the ones whose EMF emission level is under a threshold for outdoor environment. That says, while the typical downlink connects a UE to the AP with the strongest received signal strength

(RSS), the proposed protocol selects one among the APs keeping the human EMF exposure at safe levels. As there is no alternative BS in the indoor environment, we depend on reducing the transmit power and antenna arrays in the AP to reduce the EMF exposure level for an indoor scenario. Also, we highlight the main advantages and disadvantages of our indoor protocol based on transmit power reduction and antenna array reduction.

2.4 Chapter Summary

In this chapter, a literature review related to this thesis is presented. The present existing guidelines for PD and SAR and the current statement of the regulatory authorities are presented in Section 2.1. Different reduction schemes that have been adopted in the literature for the purpose of human EMF mitigation at high frequencies are mentioned in Section 2.2 and the contribution of this thesis work is highlighted in Section 2.3.

CHAPTER 3
SYSTEM MODEL

This section describes the system setting for the three cellular communications network that forms the basis for the analysis of human EMF exposure at outdoor and the two cellular networks that are employed for analysis at indoor.

3.1 System Setting for Outdoor

This section describes the system setting for a cellular network that forms the basis for the analysis of human EMF exposure. Our analysis for the 5G outdoor environment is based on the 3GPP Release 15 [32], one of the promising technical specifications for 5G. We compare the EMF exposure level in a 5G system between the proposed protocol that selects an AP for a UE keeping the PD value below the FCC or ICNIRP's guideline of 10 W/m^2 for the general public, and the typical protocol which connects a UE to the AP with the highest RSS. This research work does not consider the more recent set of exposure limits proposed by IEEE because these limits have not been adopted in any regulatory requirements so far [21]. For highlighting the performance at the outdoor environment of our proposed 5G protocol with the typical protocol and the concurrent systems, this paper chooses to compare the 5G to the 3.9G [33] and 4G [34].

We chose the frequency spectrum of 28 GHz as a potential candidate for 5G New Radio (NR). Since both Release 14 and Release 15 (which provides more definitions for 5G) share the same technical specifications in [32], this work, in other sense, represents also the performance of Release 15. The parameters of the three systems are summarized in Table 3.1.

Commonly for 5G NR, 4G, and 3.9G, this paper assumes a fully loaded network in order to understand the worst possible EMF exposure. Specifically, none of the three systems are supposed to adopt the power control nor adaptive beamforming, which can reduce the number of UEs that are being served at a certain time instant. The reason for such a worst-case assumption is to provide a 'conservative' suggestion on human safety, which leaves some safety margin as discussed in [23].

Our model for a 5G network at outdoor environment is illustrated in Fig. 3.1. Although we chose 28 GHz as the carrier frequency to design our model, the analysis framework can be extended and the performance can be demonstrated for any other standards of networks, following the same methodology. The model has random UE locations and random line-of-sight (LoS) for each and every UE to make it a more realistic case.

Note that a 3.9G system is composed of larger cells wherein a single BS can provide coverage up to several kilometers (km), which is in contrast to a 5G network operating at higher frequencies (e.g., 28 GHz), adopting a relatively smaller cell size [32]. As such, in 5G, the same area is covered by a larger number of APs with denser deployment in order to provide higher RSS at a UE.

Table 3.1: Parameters for 5G NR, 4G and 3.9G

Parameter	**Value**		
	Release 15 (5G NR)	Release 12 (4G)	Release 9 (3.9G)
Carrier frequency	28 GHz	2 GHz	1.9 GHz
System layout	UMa, UMi [32]	UMa, UMi [34]	UMa, UMi [33]
Inter-site distance (ISD)	500 m (UMa) and 200 m (UMi)	Same as 5G	3 Km (UMa) and 1 Km (UMi)
Cell sectorization	3 sectors/site	3 sectors/site	3 or 6 sectors/site
Bandwidth	850 MHz	20 MHz	20 MHz
Max antenna gain	8 dBi per element	8 dBi per element	17 dBi
Transmit power	35 dBm	49 dBm (UMa) and 44 dBm (UMi)	43 dBm
AP's number of antennas ($\lambda/2$ array)	8×8	4 [35]	4
AP antenna height	25 m (UMa) and 10 m (UMi)	25 m (UMa) and 10 m (UMi)	32 m
Duplexing	Time-division duplexing (TDD)		
Transmission scheme	Singler-user (SU)-MIMO		
UE noise figure	9 dB		
Temperature	290 K		

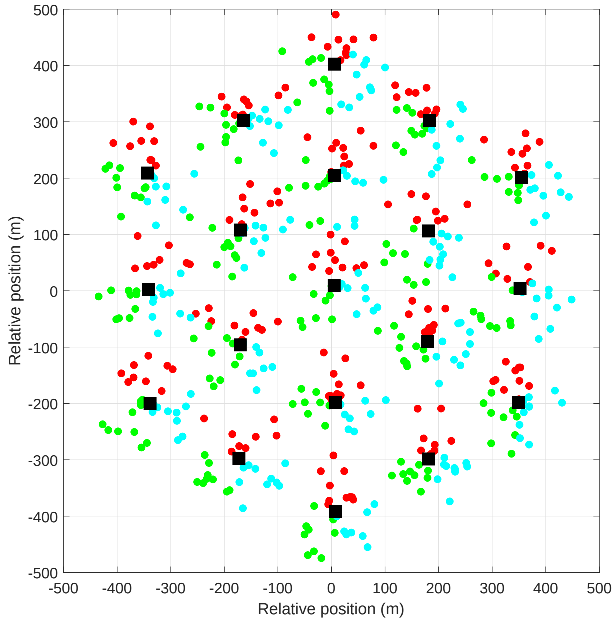

Figure 3.1: A snapshot of 'one drop' of the 5G topology (blue, green, and red dots denote UEs in each sector; and black squares represent APs.)

3.1.1 5G NR and 4G

Path Loss

Our model for 5G NR and 4G both consist of 19 sites each having 3 sectors. Our analysis suggests Rural Macro (RMa) scenario does not introduce any significant increase in the exposure level in 5G compared to the concurrent systems due to its higher inter-site distance (ISD) and BS antenna height [32]. For the terrestrial propagation between an AP and a UE, the scope of this work is limited to two scenarios: Urban Macro (UMa) and Urban Micro (UMi). The ISD is 200 meters (m) for UMi and 500 m for UMa and each sector is assumed to have 10 active UEs.

Antenna Beam Pattern

For a 5G NR and 4G AP, the attenuation patterns of an antenna element on the elevation and azimuth plane are given by [32][34]

$$A_a(\phi) = \min\left\{12\left(\frac{\phi}{\phi_{3db}}\right)^2, A_m\right\} \text{ [dB]} \tag{3.1}$$

$$A_e(\theta) = \min\left\{12\left(\frac{\theta - 90^\circ}{\theta_{3db}}\right)^2, A_m\right\} \text{ [dB]} \tag{3.2}$$

where ϕ and θ are angles of a beam on the azimuth and elevation plane, respectively; $(\cdot)_{3db}$ denotes an angle at which a 3-dB loss occurs which is 65°. Then the antenna element pattern that is combined in the two planes is given by

$$A(\theta, \phi) = \min\left(A_a(\phi) + A_e(\theta), A_m\right) \text{ [dB]} \tag{3.3}$$

where A_m(=30 dB) is a maximum attenuation (front-to-back ratio) [32], but it can be higher in practice. Finally, an antenna gain that is formulated as

$$G(\phi, \theta) = G_{max} - A(\phi, \theta) \text{ [dB]} \tag{3.4}$$

where G_{max} is a maximum antenna gain. The maximum transmitter antenna gain can be expressed as

$$G_{max} = G_{ele} + 10\log_{10}(N) \tag{3.5}$$

where G_{ele} is the max antenna gain per element and N is the AP's number of antennas.

3.1.2 3.9G

Path Loss

A cellular network operating on 3.9G is designed to form a cell radius of 1500 m and 500 m, which results in an ISD of 3 kilometers (km) and 1 km for UMa and UMi, respectively [33]. This paper calculates the received power in a downlink, following the path loss models provided in [33] for UMa and UMi.

Antenna Beam Pattern

The antenna radiation pattern for a 3.9G BS is also given as Eqs. (3.1) and (3.2). However, unlike at a 5G AP, θ_{3db} and A_m for a 3.9G BS are given as 35° and 23 dB, respectively.

3.2 System Setting for Indoor

In this section, we outlined the system model for the analysis in the indoor environment. The scope of this thesis work for 5G at indoor environment is limited to only an indoor office environment for the comparison of the human EMF exposure. The analysis of a 5G indoor environment is performed following the 3GPP Release 15 [32] which provides detailed specifications for indoor network. The center frequency is chosen as 60 GHz with high gain beamforming features adopted in 5G. For the purpose of comparison of the human EMF exposure in indoor environment, this work chooses the Wi-Fi technology represented by IEEE 802.11n at 5 GHz [36] as one of the concurrent technologies used for indoor communications at present. The parameters of the two systems are summarized in Table 3.2.

3.2.1 5G NR

Path Loss

The 5G indoor scenario is composed of 12 APs at an indoor office environment with each of the APs placed 20 m apart. The AP's number of antenna elements is considered as 224 in total which is a set of 14 chunks of 4×4 MIMO antennas. The path loss model is considered from [32] for 5G released by 3GPP and [37] for Wi-Fi provided by the International Telecommunication Union (ITU).

Table 3.2: Parameters for 5G NR and IEEE 802.11n

Parameter	Value	
	Release 15 (5G NR Indoor)	IEEE 802.11n (Wi-Fi)
Carrier frequency	60 GHz	5 GHz
System layout	Office Indoor [32]	Office Indoor [36]
Inter-site distance (ISD)	20 m	20 m
Bandwidth	1 GHz	20 MHz
Max antenna gain	8 dBi per element	4 dBi per element
Rx antenna gain	14 dBi per element	2 dBi per element
Transmit power	24 dBm [32]	20 dBm
AP's number of antennas ($\lambda/2$ array)	14 chunks of 4×4 (total 224 [39])	4
Rx's number of antennas ($\lambda/2$ array)	4×4	3
AP antenna height	3 m	3 m
Transmission scheme	Multi-user (MU)-MIMO	
UE noise figure	6 dB	
Temperature	290 K	

Antenna Beam Pattern

The antenna radiation pattern for 5G indoor AP is also given as Eqs. (3.1) and (3.2). For 5G indoor AP, θ_{3db} is given as 65°.

3.2.2 WI-FI

Path Loss

A cellular network operating on Wi-Fi is also composed of 12 APs for an indoor environment in our analysis with each of them placed 20 m apart. But, unlike the 5G pathloss model, the pathloss for an indoor cellular network operating under Wi-Fi at 5 GHz is provided by the ITU [37].

Antenna Beam Pattern

For Wi-Fi's radiation pattern, we adopt the general linear array which is given by [38]

$$G(\theta) = G_{max} - exp(-2\pi j\delta sin\theta) \tag{3.6}$$

where δ denotes the antenna element separation distance that is half a wavelength, and θ denotes an azimuth angle. However, unlike at a 5G AP, θ_{3db} and A_m for a Wi-Fi indoor network are given as 80° and 20 dB, respectively.

3.3 Chapter Summary

We provided the system setting in this chapter for our 5G and concurrent systems for the analysis of human EMF exposure. Both the system for outdoor and indoor has been explained with detailed models and system parameters. While the outdoor model is set for 5G NR, 4G and 3.G systems, the indoor model compares the setting between the 5G NR and the concurrent Wi-Fi standards.

CHAPTER 4

PERFORMANCE ANALYSIS

We show the performance analysis of our work in this chapter. The analysis is based on the works done to evaluate the human EMF exposure from RF radiation. In our work, we sacrificed data rate to mitigate the human EMF exposure from 5G systems. However, we will show later in this thesis report that the amount of sacrifice in data rates is not severe and the data rate achieved through our proposed schemes still meet the 5G requirements.

4.1 Analysis for Outdoor Scenario

In this section, we present our analysis on the human EMF exposure in a 5G NR, a 4G and a 3.9G system. In a model like 3.9G, there may be one BS used to provide coverage to a wide area, but in a 5G scenario, the same area is covered by a number of scattered APs to provide a better reliable service with extremely fast data rates exploiting the high gain directional antennas for 5G.

Biological effects of the EMF depend on the level of energy absorbed into the human tissues. The depth of penetration into the human tissues depends on the frequency and conductivity of the tissues [18]. Above 6 GHz where 5G will likely operate, safety guidelines [19][20] are defined in terms of PD due to the shallow penetration at such high frequencies.

However, recent studies found that the PD is not as useful as SAR or temperature in the assessment of EMF exposure since SAR can display the level of EMF energy that is actually ‘absorbed’ in the body [18][27] while PD cannot. Furthermore, SAR is a more adequate metric than the temperature for far-field as the effect of temperature is likely to be dispersed over the long distance in downlinks. Therefore, this paper selects SAR as the primary metric that measures the human EMF exposure level in 5G downlinks.

4.1.1 Data Rate

The downlink performance of a system is calculated from Shannon's formula, which is given by

$$R = B\log_2(1 + \text{SNR}) \tag{4.1}$$

where R and B denote the data rate and bandwidth, respectively. Signal-to-noise power ratio (SNR) is used to determine a data rate. Note that the inter-cell interference is not considered for simplicity in the calculation as the focus of this paper is the analysis of the human exposure level, which is not influenced by the interference. In this paper, we calculate an SNR for the UEs considering all the possible locations in a sector that is formed by an AP in a 5G system and a BS in a 4G or 3.9G system. However, an accurate *three-dimensional distance* is considered with the exact heights of an AP, BS, and UE which are taken into account [32]. In other words, although the horizontal axes of the results provided in chapter 6 present all the possible locations in a cellular system, they, in fact, demonstrate three-dimensional (3D) distances with the exact vertical distances accounted.

The core part in the calculation of a bit rate is the received power that is directly determined by a path loss model provided in the specifications [32]-[34]. Here we provide an analytical framework for the signal power that is received by a UE from either an AP or a BS in a single downlink, denoted by $P_{R,ue}$. It is noteworthy that with straightforward modifications, this framework can easily be extended to an uplink received signal power also. A received signal strength in a downlink transmission of a single sector is computed by averaging over all possible downlink directions according to the position of the UE, which is given by

$$\begin{aligned} &P_{R,ue}\left(\mathtt{x}_{ue}\right) \\ &= \frac{1}{|\mathcal{R}_k^2|}\int_{\mathtt{x}_{ue}^{(k)}\in\mathcal{R}_k^2}\frac{P_{T,ap}G_{ap}\left(\mathtt{x}_{ue}\right)G_{ue}\left(\mathtt{x}_{ue}\right)}{PL_{ap\rightarrow ue}}d\mathtt{x}_{ue} \end{aligned} \tag{4.2}$$

where $\mathcal{R}_k^2$ is region of a sector and thus $|\mathcal{R}_k^2|$ is the area of a sector; $\mathtt{x}_{ue}$ is the position of a UE in an $\mathcal{R}_k^2$; $P_{T,ap}$ is transmit power of an AP; G_{ap} and G_{ue} are the antenna beamforming gains of an AP and a UE, respectively, in a downlink transmission based on (3.4); $PL_{ap\rightarrow ss}$ is the path loss between the AP and the UE.

4.1.2 Human EMF Exposure

PD is defined as the amount of power radiated per unit volume at a distance *d* [17], which is given by

$$\text{PD}\left(d\right) = \frac{\left|E\left(d\right)\right|^2}{\rho_0} \quad [\text{W/m}^2] \tag{4.3}$$

where $E\left(d\right)$ is the incident electric field's complex amplitude and ρ_0 is the characteristic impedance of free space. It can be rewritten by using the transmitter's parameters as

$$\text{PD}\left(d,\phi\right) = \frac{P_T G_T\left(d,\phi\right)}{4\pi d^2} \tag{4.4}$$

where P_T is a transmit power; G_T is a transmit antenna gain; d is a BS-UE distance (m).

At high frequencies such as 28 GHz, most of the energy of a signal incident on human tissue is deposited into the thin surface of skin [29]. The SAR is a quantitative measure that represents the power dissipated per body mass. In other words, SAR is defined as a measure of incident energy absorbed per unit of mass and time and thus quantifies the rate at which the human body absorbs energy from an electromagnetic field. The local SAR value at a point p measured in W/kg [29] can be expressed as

$$\text{SAR}\left(\text{p}\right) = \frac{\sigma\left|E\left(\text{p}\right)\right|^2}{\rho} \quad [\text{W/kg}] \tag{4.5}$$

where σ is the conductivity of the material and ρ is the density of the material (kg/m^3). The SAR value in terms of d for cellular communications system, which is also a function of ϕ [31], can be expressed as

$$\text{SAR}\left(d,\phi\right) = \frac{2PD\left(\phi\right)T\left(\phi\right)m\left(\phi\right)}{\delta\rho} \tag{4.6}$$

where T is the power transmission coefficient [29], and δ is the skin penetration depth (m) at 28 GHz [27]. The function $m\left(\phi\right)$ [29] is dependent on the tissue properties of dielectric constant (ϵ^{*}).

The same Eq. (4.6) at a point on the air-skin boundary [31] can be rewritten as a function of PD(d,ϕ) as

$$\mathrm{SAR}\left(d,\phi\right)=\frac{2\mathrm{PD}\left(d,\phi\right)\left(1-R^{2}\right)}{\delta\rho} \tag{4.7}$$

where R is the reflection coefficient [17], 1 $\mathrm{g/cm^{3}}$ is used for tissue mass desnsity ρ, and 10^{-3} m is used for skin penetration depth δ [27].

Note that d and ϕ depend on the position of a UE in a cell. Therefore, similar to Eq. (4.2), in order to evaluate over all the possible UE positions in a cell, the SAR is calculated as an average over the area of a 'sector' in a cell, which is given by

$$\mathbb{E}[\mathrm{SAR}\left(\mathrm{x}_{ue}\right)]=\frac{1}{|\mathcal{R}_{k}^{2}|}\int_{\mathrm{x}_{ue}^{(k)}\in\mathcal{R}_{k}^{2}}\mathrm{SAR}\left(\mathrm{x}_{ue}\right)d\mathrm{x}_{ue} \tag{4.8}$$

where uniform distribution of UEs on each of the X- and Y-axis of each sector, $\mathcal{R}_{k}^{2}$, was considered.

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. 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 [17][18]. Hence, PD is not likely to be as useful as SAR for assessing safety from a cellular communications system.

In order to accurately study a high frequency signal propagation and absorption in the human body, investigation on the parameters related to dielectric measurements on human skin are necessary. Specifically the values of the parameters, ρ, ϵ^*, δ, T, and $m(\phi)$ are obtained from prior related work [26][27][29][32][40].

4.1.3 Chapter Summary

We presented the human EMF exposure analysis of our research in this chapter. The exposure measurement metric SAR can be derived from a PD which we have shown in this chapter. Also, to understand the downlink performance for both the indoor and outdoor scenario at 5G, we presented the analysis performed in terms of data rate. It should be noted that we used the free-space path loss models to perform the analysis of the exposure from previous studies in the literature.

CHAPTER 5

PROPOSED PROTOCOL

The comparison results provided in the next section suggest that the EMF exposure level from the 5G exceeds the concurrent exposure guidelines for a very close separation between AP and UE for both outdoor and indoor, but the EMF exposure from a 5G cellular system remains on a high throughout the entire network. To reduce the effect of exposure from the 5G network, we proposed 3 novel protocols- one for the outdoor and two for the indoor scenario. It is noteworthy to mention that our proposed protocol for outdoor is published in the Journal of *Springer Annals of Telecommunication*.

5.1 Proposed Protocol for Outdoor

As will be discussed in the next chapter, our results show that 5G causes a higher level of EMF exposure than 3.9G and concurrent 4G. As a solution, we propose a downlink protocol that selects an AP for a UE, guaranteeing the EMF exposure level under a threshold. We set the threshold at 10 W/m^2, the EMF restriction guideline on PD set by the FCC [19] and ICNIRP [20].

Fig. 5.1 illustrates an example scenario of the proposed protocol. Setting the threshold 10 W/m^2 in terms of PD, the proposed protocol forces a UE to choose an AP to serve its downlink *among the ones with PD under the threshold*. The tables on the left compare the proposed protocol to a typical cellular downlink protocol. One can observe that in the proposed protocol, APs 1, 3, and 19 are excluded due to the PD levels exceeding the threshold of 10 W/m^2. In contrast, the typical downlink protocol selects the serving AP for a UE solely according to the achievable downlink rate.

Fig. 5.2 provides a flowchart for the proposed protocol. Each UE is initially served by the AP with the highest RSS, as in typical downlink protocols. However, the proposed protocol requires a UE to update the PD generated by each AP around it. This update is

Typical protocol

AP	1	2	3	4	...	19
RSS (dBm)	11	7	9	15		20

Proposed protocol

AP	~~1~~	2	~~3~~	4	...	~~19~~
PD (W/m^2)	11	6	12	8		13
RSS (dBm)	11	7	9	15		20

APs 1, 3, and 19 are excluded from the candidate due to PDs exceeding the threshold of 10 W/m^2.

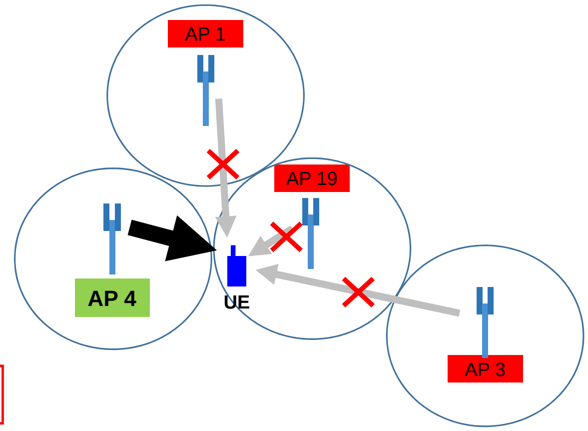

Figure 5.1: An example usage of the proposed protocol (with the threshold of 10 W/m^2)

accomplished via a downlink pilot signal–e.g., Demodulation Reference Signal (DMRS). This PD level caused by each AP is used to examine whether it violates the guideline, which is stored in the read-only memory (ROM) of each UE device according to the carrier frequencies at which it is supposed to operate. Among the APs with PDs under the guideline, one providing the maximum RSS is selected for downlink service. This AP continues to serve (i) until the UE needs to be handed over to another cell or (ii) until a timeout expires on a downlink. A timeout is set in order to periodically re-evaluate the PD and select a new AP if the current serving AP comes to violate the guideline as the UE moves in a cell.

The key rationale that the proposed protocol operates in terms of PD is two-fold. First, it can directly lead to a SAR level according to (4.7). Second, it can be derived at an AP. If derived at a UE, a separate channel would be needed to feed the SAR measured at a human user back to the serving AP. However, exploiting the fact that a SAR is directly computed from a PD, an AP can measure its PD via estimation of the distance to UE. This estimation can be performed by inferring the distance from the power of a received control signal–viz., via Channel Quality Indicator (CQI) in Physical Uplink Control Channel (PUCCH). Such

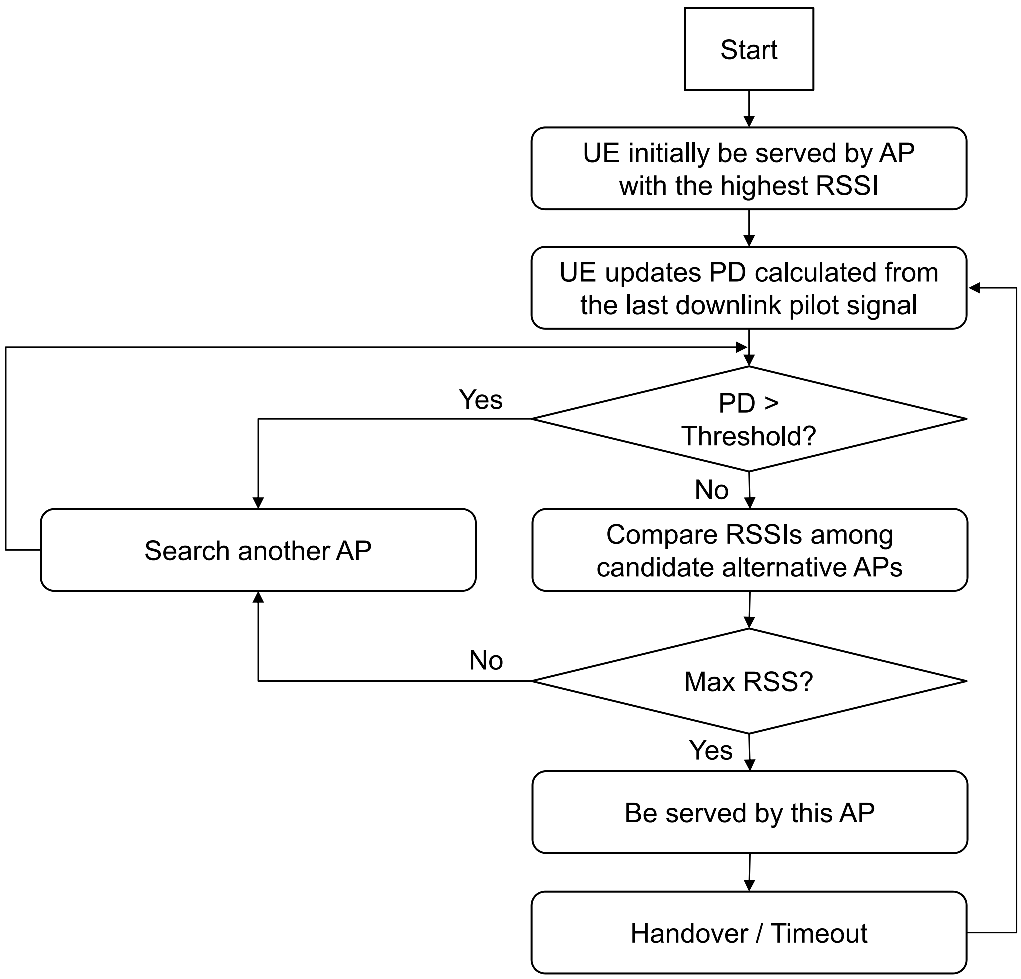

Figure 5.2: Flowchart of the proposed protocol for a UE

'piggybacking' can reduce the feedback overhead between a UE and its serving AP, which in turn results in efficient cellular networking.

5.2 Proposed Protocol for Indoor

Unlike our proposed protocol in a 5G outdoor scenario in which a UE selects an AP based on the PD threshold of 10 W/m^2 while the serving AP violates the guideline, the protocol we propose for the indoor office environment is dependent on the reduction of resources such as, AP transmit power or the number of antenna elements in the antenna configuration. The key rationale behind this proposal stems from the fact that there is no other AP to which a UE can connect itself if the serving AP violates the guideline at an indoor environment. We consider an office environment where no other network protocol like femtocell or picocell is deployed.

First, we show our proposed protocol for indoors reducing the transmit power by the APs. The reduction of transmit power will reduce the performance in downlink which is represented by the downlink data rate at a UE.

Second, we show the mitigation process of human EMF exposure by the reduction in the number of antenna elements which also degrades the data rate performance. However, we will show in the next chapter that none of these proposed protocols will serve the UE under the 5G data rate requirements even after sacrificing in downlink data rates to keep the human users safe from the higher amount of EMFs generated in 5G.

5.2.1 Mitigation of EMF Exposure by Reduction in Transmit Power

We consider an indoor office scenario where there is no alternative AP to connect a UE when the EMF exposure exceeds the threshold from a serving AP. We set the maximum PD value received from a Wi-Fi network as the threshold for EMF mitigation in 5G so that the maximum exposure level in a 5G network does not cross the level of that from concurrent Wi-Fi systems. In other words, our threshold in the first step is chosen such that the maximum EMF exposure level from a 5G network remains the same as the concurrent Wi-Fi network. Our protocol reduces the transmit power by 1 dBm every time the PD level exceeds the threshold. The maximum transmit power which provides the UE with a PD value less than the threshold is chosen as the serving transmit power for that specific UE.

However, we will show in the next chapter that this threshold leaves a large margin to increase in the EMF exposure level in terms of both PD and SAR if the present guidelines by FCC are considered to be a safe exposure compliance level. Thus, in the second step, we increased the transmit power up to a level so that the current FCC guideline on SAR is not violated. In other meaning, we increased the data rate of the UEs at the indoor environment compared to those achieved when the maximum PD from Wi-Fi was chosen as the threshold. Also, it is noteworthy to mention that FCC or ICNIRP do not have an exposure guideline for SAR in terms of far-field based on a belief that SAR is not effective to be considered in a far-field scenario. But, as SAR can effectively measure the absorption of power into the human body, we consider this metric as a key measurement metric for determining the human EMF exposure from RF radiations in cellular networks.

Our simulation results found that SAR (near-field guideline) is the only measurement metric that was violated by some UEs in an indoor office environment operating under 5G, while the PD level for all the UEs remains under the current FCC guideline. Thus, we chose the near-field SAR guideline set by the FCC as our threshold for the mitigation protocol in the second step.

5.2.2 Mitigation of EMF Exposure by Reduction in Antenna Elements

This protocol minimizes the serving antenna element numbers at the AP for a UE until the EMF level falls to a value lower than the threshold. Reduction in the number of serving antenna elements results in a decrease in the antenna gain which lowers the PD level according to Eq. (4.4). Any reduction in the PD eventually reduces the SAR level following Eq. (4.7). We consider a total of 224 antenna array elements at the indoor AP [39] configured in a 4×4 MIMO pattern. We refer each of these 4×4 MIMO antenna elements as chunks. The maximum number of a chunk is considered as the serving antenna elements that provide a UE with an exposure value lower than the threshold.

The greatest advantage of considering such a MIMO antenna configuration is the flexibility of serving different UEs with different antenna configurations at the same time. Like the work performed in 5.2.1, we again considered two different thresholds for the mitigation

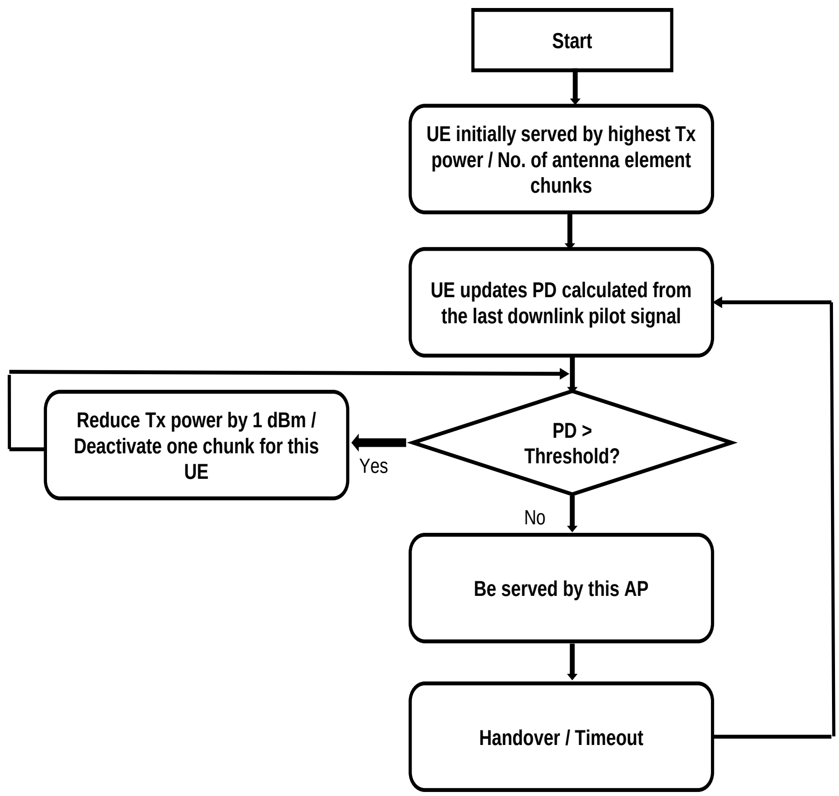

Figure 5.3: Flowchart of the proposed protocol for a UE at indoor scenario

of human EMF exposure by minimizing antenna chunks in two steps–first, considering the maximum PD achieved in a Wi-Fi as the threshold for 5G and then, considering the SAR near-field guideline as to the threshold. The second step which considers SAR near-field guideline as the threshold is performed by choosing a PD value which results in a maximum SAR level of 1.6 W/kg [19]. Fig. 5.3 shows a flowchart of our proposed protocol in the indoor office environment for the 5G network.

5.3 Summary

In this chapter, we proposed our protocols for minimizing human EMF exposure. The EMF exposure mitigation scheme for the outdoor scenario provided in this chapter is based on the selection of alternative APs if the serving AP violates the exposure guideline. The indoor environment is considered such that there is no alternative APs for the UEs if the serving AP violates the EMF threshold. Our findings illustrated that decreasing the transmit power or the BS antennas can effectively keep the human EMF exposure level under the safety margin.

CHAPTER 6

NUMERICAL RESULTS

This chapter presents our simulation results for EMF exposure in 5G with a comparison to the concurrent technologies for both outdoor and indoor scenarios. We represent the (i) evaluation of human EMF exposure for the considered scenarios; (ii) effectiveness of our proposed EMF exposure mitigation protocol; and (iii) evaluate a possible negative impact of the proposed protocol on the 5G data rates.

6.1 OUTDOOR

In this section, we analyze our findings and compare the results between the three cellular systems (specified above) to have a clear view of the maximum threats possible from a 5G network.

6.1.1 DATA RATE

We consider an antenna array size of 8×8 for 5G analysis. The BS antenna size for 4G [35] and 3.9G both consist of 4 antenna elements as specified in Table I.

Fig. 6.1 shows the data rates that can be achieved in a 5G NR, a 4G and a 3.9G systems to represent the downlink performances at outdoors. It can be seen that a UE in both 5G scenarios can yield a maximum downlink data rate above 15 Gbps. However, this performance may decrease in a practical case when interference is considered.

It should be emphasized in Fig. 6.1 that in spite of the disadvantage in propagation due to the higher carrier frequency, a 5G NR system presents approximately 15-times higher downlink rates compared to a 4G system and approximately 20-times higher downlink rates compared to a 3.9G system. The main rationale behind such a significant outperformance is the beamforming antenna structure with high gains and smaller ISD in a 5G NR system.

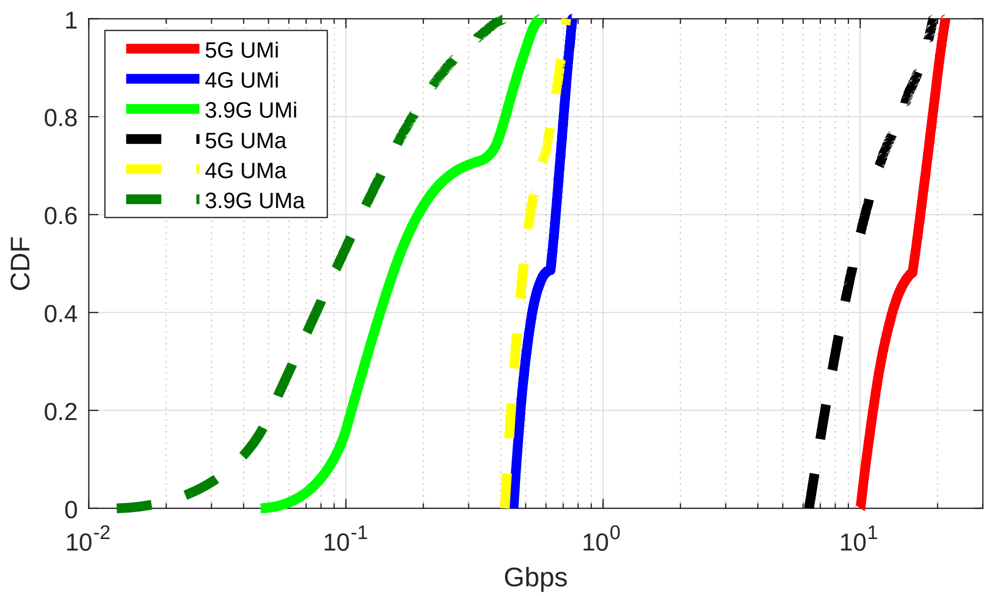

Figure 6.1: CDF versus Bit rate for 5G, 4G and 3.9G

It is thus evident that the 5G beamforming technology provides significantly better performance to the consumer as it provides better signal strength with higher data transmission capabilities at the user end.

6.1.2 Evaluation of Human EMF Exposure

Now we show that even considering such shallow penetration depth due to high frequencies, a 5G downlink EMF emission can cause higher exposure than the concurrent 4G or 3.9G systems. Figs. 6.2 and 6.3 show the comparison in terms of PD and SAR for the human exposure to EMFs in downlinks. Each result specifies a path loss scenario (UMa or UMi) and the measurement metric (PD or SAR). Note that every result is an average taken over 10,000 drops of UE distribution in each sector or cell according to Eq. (4.8). As described in Section 4.1.2, the UEs are uniformly distributed on a two-dimensional space $\mathcal{R}_k^2$ representing a sector. The results for 5G UMa and UMi are identical with the only exception that the PD or SAR bounces back to top again after 100 m for UMi scenario because

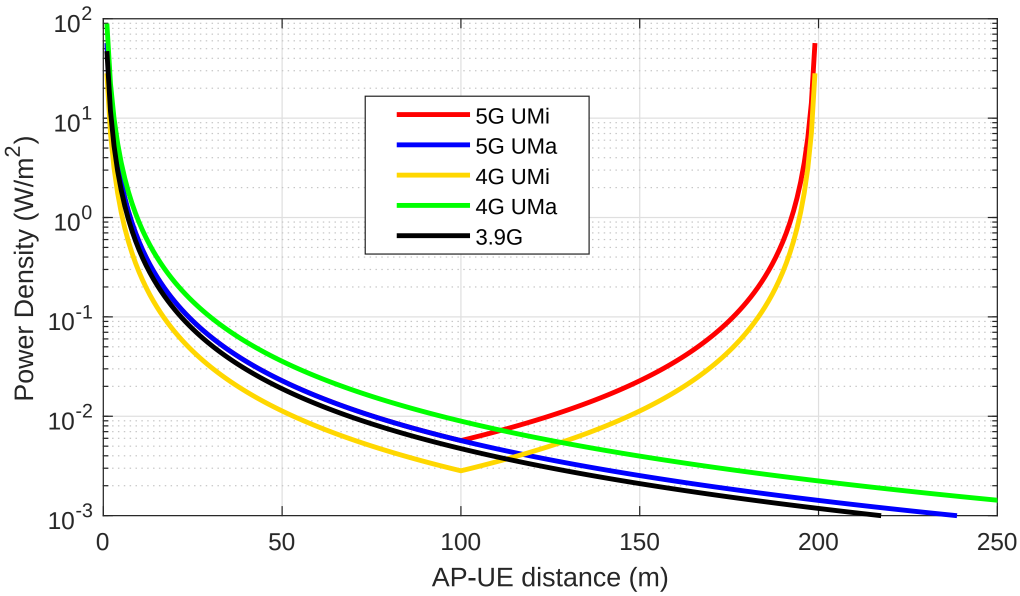

Figure 6.2: PD versus AP-UE distance

of its ISD of 200 m, and the values for UMa will bounce back after 250 m as the 5G UMa has an ISD of 500 m [32]. The same condition applies for 3.9G systems also depending on its ISD. But, the values for the 4G system are different in the UMa and UMi scenario because of the different transmit power adopted at the BSs as provided in Table 3.1.

In Figs. 6.4 and 6.5, we take a zoomed-in look of Figs. 6.2 and 6.3 for closer investigation of how each of the wireless systems is distinguished in terms of PD and SAR at a shorter distance from a BS. It can be seen that a downlink EMF emission can cause approximately 10-times higher exposure than concurrent 4G UMa and almost 15-times higher exposure than 4G UMi in terms of SAR level in 5G systems (Fig. 6.5) while the PD level can still remain on the lower side (Fig. 6.4). The rationale behind such an occurrence is (i) the higher concentration of EMF energy per beam via the adoption of larger phased array and (ii) the adoption of reduced transmit power for small cells [41], one key enabler of the future 5G NR using massive multiple-input multiple output (MIMO) antennas. The reduced transmit power feature of a 5G NR system leads to a smaller effective isotropic

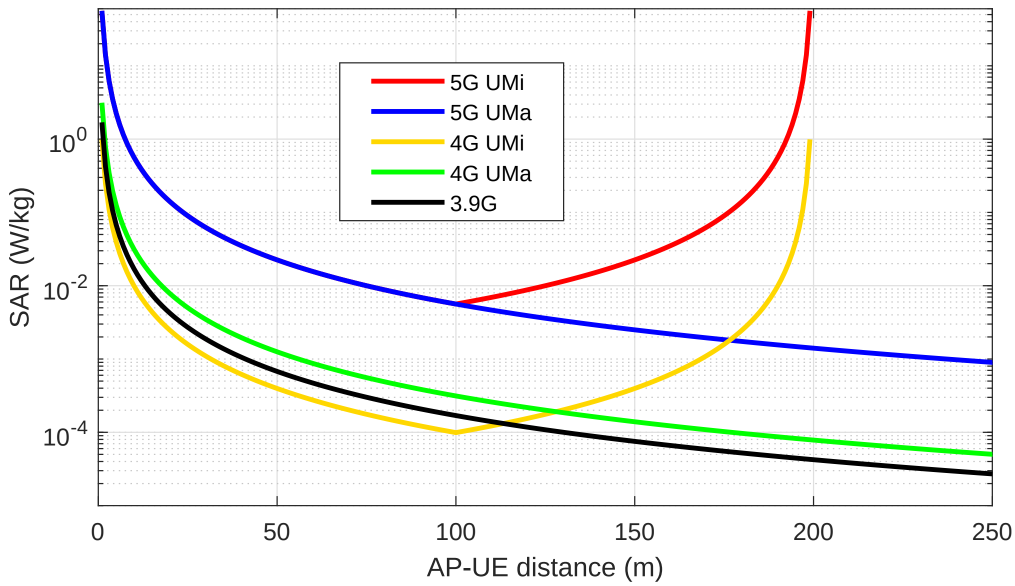

Figure 6.3: SAR versus AP-UE distance

radiated power (EIRP) [32] than a 4G system. Note that 4G UMa has the highest PD because of its higher transmit power at the BS resulting in the highest net EIRP than the other systems. On the other hand, 4G UMi has the lowest PD and SAR because of the adoption of lower antenna elements (compared to 5G NR) and lower transmit power (compared to 4G UMa) at the BS. In other words, the lower antenna elements at the transmitter result in a smaller transmitter gain for 4G UMi according to Eq. (3.5) and finally resulting in the lowest PD following Eq. (4.4), which gives the lowest SAR following Eq. (4.7). The work in this paper is distinguished from our previous work in [10], which showed the EMF exposure for 5G when very high transmit power is adopted at the APs.

As mentioned that it still remains inconclusive in the literature which of PD and SAR is more appropriate to represent the human EMF exposure level in far-field propagations, this paper claims that *SAR should not be excluded* in the measurement of human EMF exposure in 5G downlinks. This is supported by the observation that in 4G (with smaller phased arrays) and 3.9G (with a larger ISD) yield a longer propagation that is sufficient fall

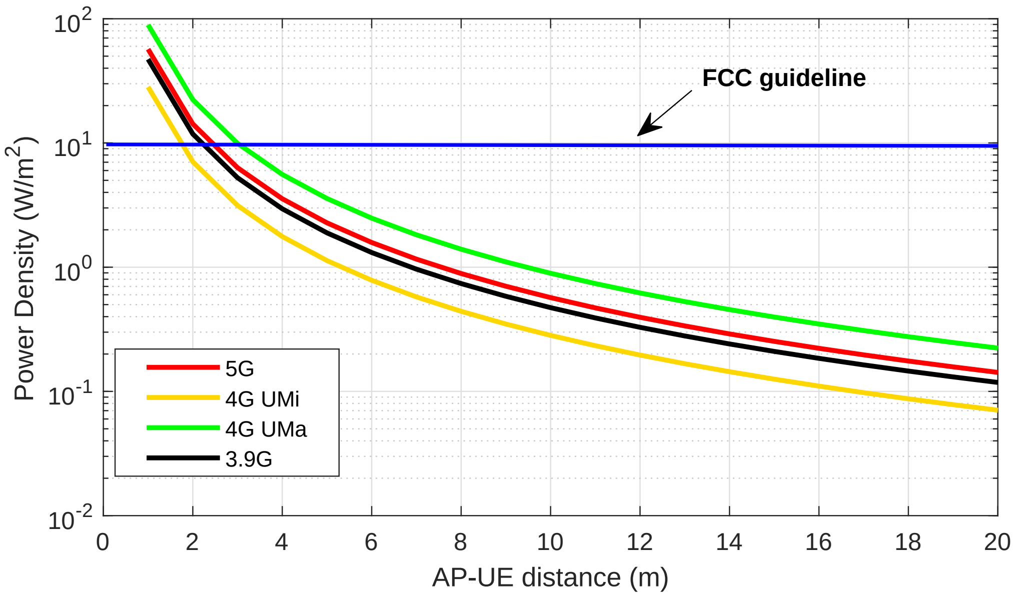

Figure 6.4: PD versus AP-UE distance (zoomed in view)

down to a low enough SAR. The 5G beamforming antenna radiations with higher gains, larger phased arrays, and smart antenna characteristics keep the SAR value higher in more areas in a network than a 3.9G or 4G.

The results provided in Figs. 6.4 and 6.5 have a deep significance. The current exposure guidelines are set for PD at 10 W/m^2 for the general public [19][20]. For SAR, the guidelines are set at 1.6 W/kg by FCC [19] and 2 W/kg by ICNIRP [20] for 'near-field' exposure. To the best of our knowledge, there is no guideline set in terms of SAR in far-field exposure [17] so far based on a belief that SAR does not have a significant effect on the human body in far-field. But our results suggest that the human users in 5G can be exposed to higher SAR than the present systems at every point in a network. Even the available near field SAR exposure guideline can be violated at a close AP-UE distance. Therefore, this paper urges the regulatory authorities to set SAR guidelines for 5G systems at far-field exposure also for frequencies above 6 GHz. Also, the minimum AP-UE distance should be maintained at least 6 m for 5G and further space should be left for a conservative operation

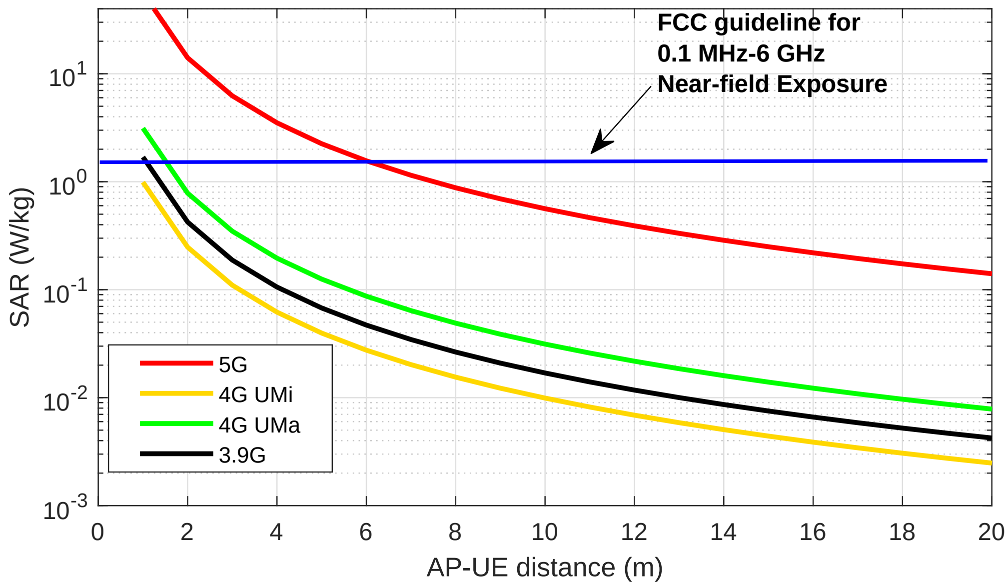

Figure 6.5: SAR versus AP-UE distance (zoomed in view)

regarding human safety.

6.1.3 Mitigation of Human EMF Exposure

Reduction in SAR

Here, we show the performance of our proposed protocol for the mitigation of human EMF exposure. Unlike the previous results, cumulative distribution function (CDF) representation is adopted here to illustrate the view over the entire 19-cell layout. As we pointed out that the PD from the 5G systems can be lower than the existing 4G network, our human EMF mitigation protocol only focuses to reduce the exposure in terms of SAR which remains higher throughout the network for 5G compared to the concurrent systems. We assume that 5G is not going to cause excessive harm to the human body in terms of PD as the concurrent 4G is operating with higher PD values at present with no negative impacts on the human health.

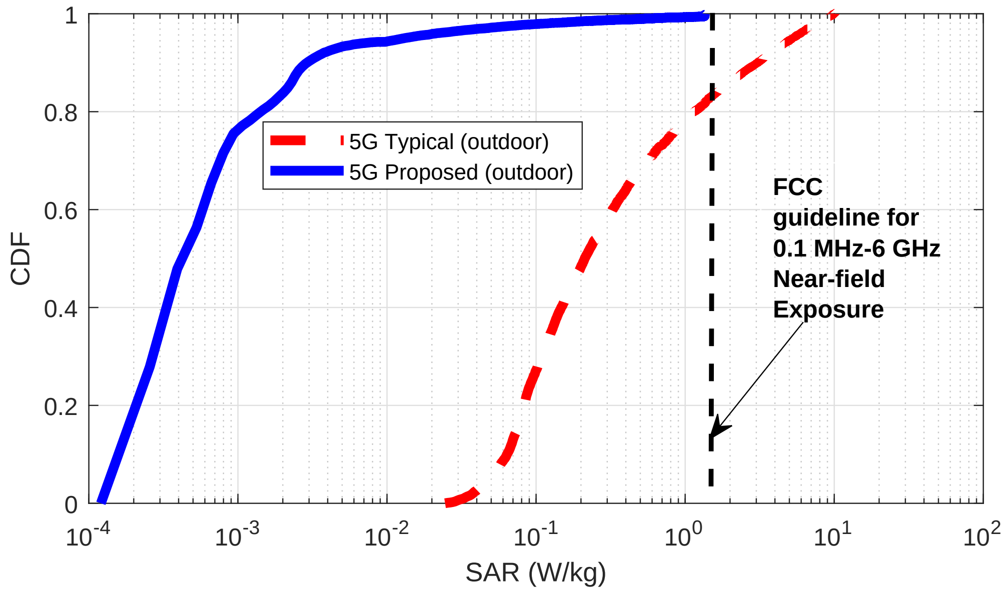

Figure 6.6: Mitigation of SAR in 5G (outdoor) with application of the proposed protocol

For the mitigation of human EMF exposure at an outdoor scenario, we consider the SAR near-field exposure guideline of 1.6 W/kg, set by the FCC. It is already mentioned that there is no guideline for SAR in far-field yet because of the belief that SAR is not significant to be considered when the AP-UE separation distance is higher.

As SAR is a more informative metric than PD, this work finds the necessity of considering SAR in downlinks for high frequencies. Fig. 6.6 suggests that our proposed protocol is capable to reduce the SAR level for 5G throughout the network. Further, we hope that this result can urge swift movement for setting up guidelines for downlinks in terms of SAR at higher frequencies such as 28 GHz. Previously, we showed that both UMa and UMi in 5G provide the same amount of EMF exposure in terms of PD and SAR as the transmit power and antenna gain remains fixed for both these scenarios. In other words, Fig. 6.6 conveys the human EMF mitigation for both UMa and UMi scenarios.

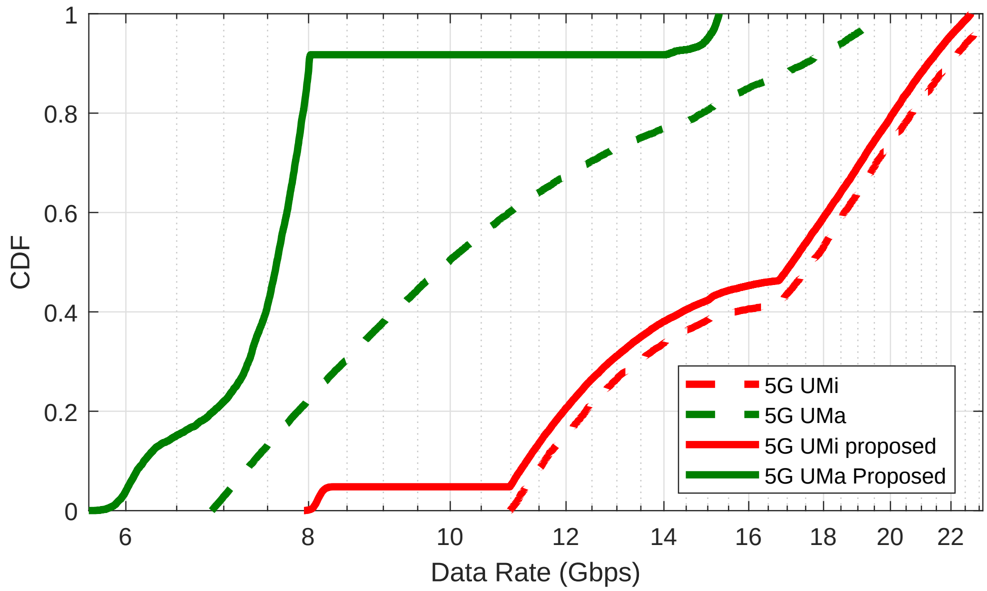

Figure 6.7: Impact of the proposed protocol in data rate

Sacrifice in downlink data rates caused by proposed protocol

Fig. 6.6 shows the comparison of downlink data rates that can be achieved between the typical 5G systems and the proposed 5G EMF mitigation scheme. The same as in Figs. 6.6, CDF is adopted to present a view over the 19-cell layout. It can be seen that our proposed protocol sacrifices data rates as it prioritizes the SAR to the data rate in selection of the serving AP for a UE, as illustrated in Fig. 6.7.

6.2 Indoor

We extend our work from outdoor to the indoor environment for the analysis of exposure to the human body from future 5G communications. In this section, we present our findings and the performance of the proposed protocol with comparison to the existing Wi-Fi system as a representative of the concurrent technology.

6.2.1 Human EMF Exposure

The results of the comparison of the human EMF exposure from a 5G indoor office scenario [32] and Wi-Fi [36] are provided in Fig. 6.8 and 6.9. It can be depicted from these two figures that unlike the results obtained for outdoors, both PD and SAR for the 5G can impose higher levels of exposure than the concurrent Wi-Fi network. However, the PD level from a 5G indoor scenario does not cross the regulatory guideline even considering the worst possible assumptions. But to make sure that the 5G network does not provide a higher level of exposure than the Wi-Fi, we set the maximum PD obtained from the Wi-Fi as the threshold for our EMF mitigation protocol.

We considered two types of mitigation procedure- one by the reduction of transmitting power and the other by reducing the number of antenna elements at the AP's transmitting antenna. For the first case, we reduced the transmit power by 1 dBm each time when the network exceeds the threshold for any UE. When the exposure level for PD falls below the threshold, this UE is served with this PD value until a time-out occurs.

Fig. 6.8 depicts that setting the maximum PD level obtained from the Wi-Fi network as the threshold for our EMF exposure mitigation scheme, there remains some extra margin for increasing the PD for 5G. In other words, we can increase the data rate even further by considering some more exposure in the human body that remains significantly lower than the guideline. For this approach, we choose the available near-field SAR guideline of 1.6 W/kg by the FCC for frequencies from 0.1 to 6000 MHz [19] in Fig. 6.9 and followed the same procedure of reducing the EMF exposure by the reduction in transmit power.

Second, we reduced the EMF exposure by minimizing the number of antenna arrays in the AP's antenna configuration and followed the similar threshold mentioned above. Our analysis suggests, even considering only 1 antenna element at the AP's transmit antenna, the 5G EMF exposure in terms of PD is still higher than the maximum EMF exposure obtained from the Wi-Fi systems. The main rationale for this occurrence is the high gain

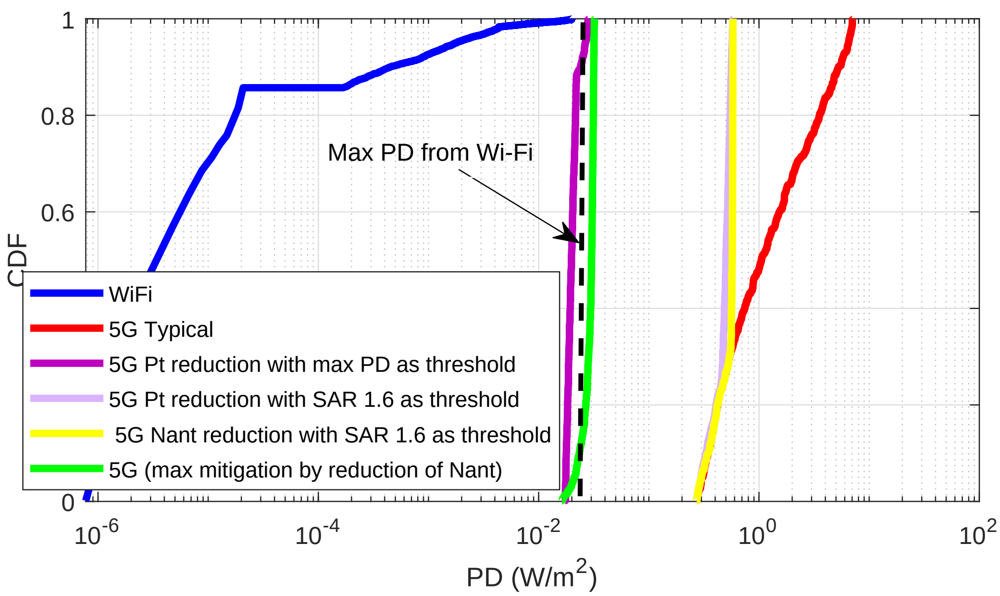

Figure 6.8: Mitigation of PD in 5G (indoor) with application of the proposed protocol

beamforming antenna configuration in a 5G network which elevates the exposure level even with such shallow penetration at very high frequencies., such as 60 GHz. Thus, the minimum exposure from a 5G network cannot match even with the maximum exposure obtained from a Wi-Fi network by the process of minimizing transmit antenna arrays. Fig. 6.8 and 6.9 show the maximum possible reduction of exposure in terms of PD and SAR respectively, by minimizing antenna elements (green curve).

The Figs. in 6.8 and 6.9 highlights the significance of our proposed protocols for effectively minimizing the human EMF exposure in an indoor office scenario. One can clearly identify that the reduction in transmit power or antenna array are almost the same approach as both of these techniques try to reduce the net EIRP at a UE. The trade-off for this approach is the sacrifice in data rates which we discuss below.

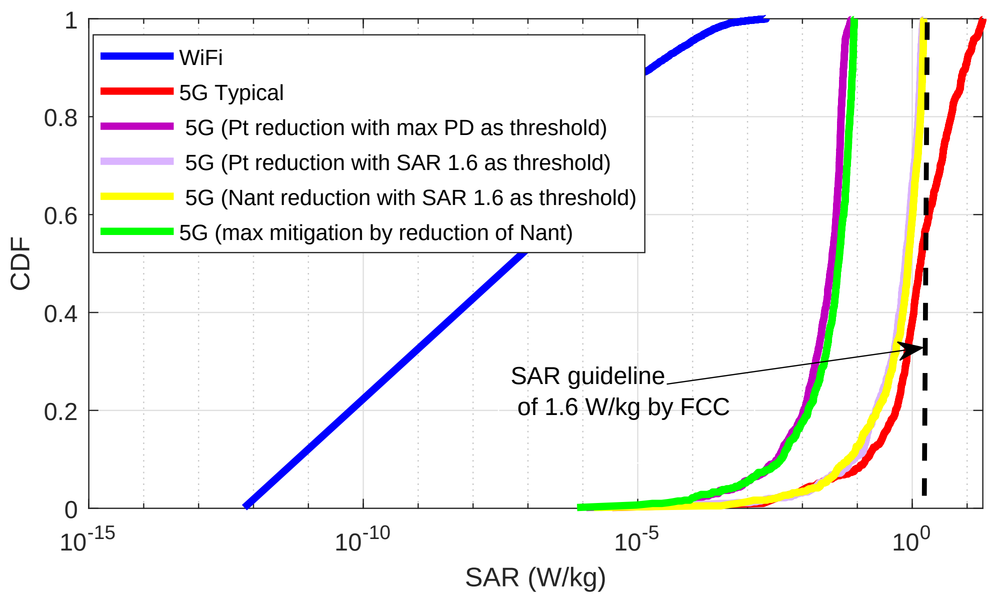

Figure 6.9: Mitigation of SAR in 5G (indoor) with application of the proposed protocol

6.2.2 Data Rate

We finally show the data rate comparison between a typical 5G indoor office network, a concurrent Wi-Fi network and our proposed protocols in Fig. 6.10.

It should be noted that we considered an antenna array size of 14×16 for 5G analysis [39], which results in 224 antenna elements in the transmit AP. We consider 4 antenna elements for both AP and receiver antenna configuration for Wi-Fi [36]. Fig. 6.10 clearly shows that even after several Gbps reductions in the proposed protocols from the typical 5G network, where no EMF exposure mitigation scheme is adopted, the proposed schemes can still provide a very high data rate at the user end than the concurrent system. In fact, the requirement for 5G data speed can be achieved even after adopting our proposed schemes.

Thus, our proposed techniques will keep the 5G network fully operational while keeping the human users under a safe communications network.

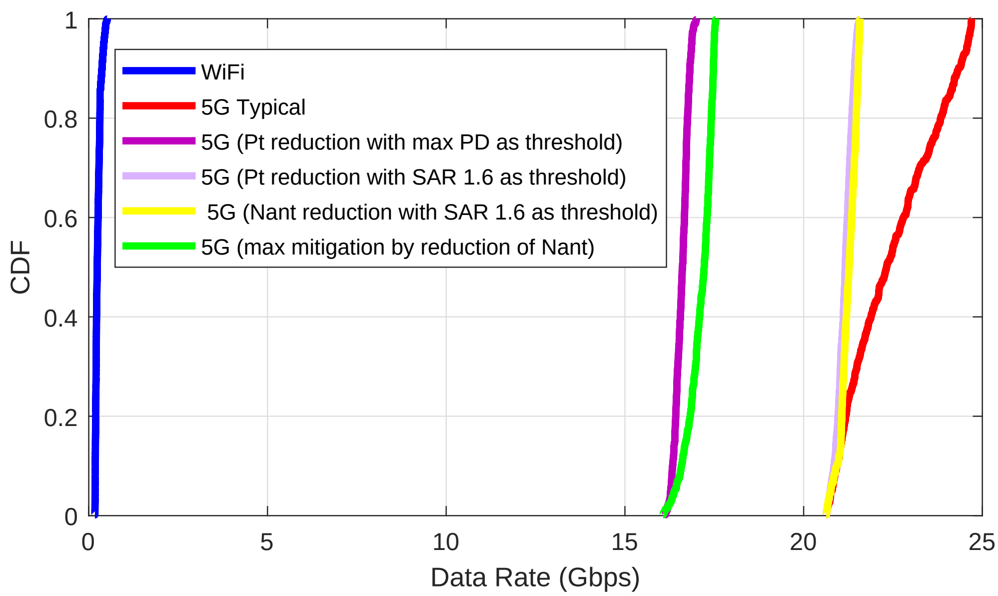

Figure 6.10: Data rate comparison with application of the proposed protocol (indoor)

6.3 Chapter Summary

In this chapter, we presented our findings and showed the performance of our proposed schemes for 5G indoor and outdoor downlink communications. Each of the results was verified using MATLAB. First, we explained the necessity of a human EMF mitigation scheme by representing the comparisons between the 5G networks, where no mitigation schemes are adopted with concurrent cellular technologies. Then the performance of our EMF mitigation schemes is presented showing the effectiveness to reduce EMF exposure while keeping the service quality within 5G requirements.

CHAPTER 7

CONCLUSION

This chapter summarizes the contributions of this research work and suggests some possible future directions. This thesis consists of 3 parts. The first part (Chapter 3 and 4) present the evaluation of the human EMF exposure from a 5G downlink communications at both outdoor and indoor scenarios. The evaluations were performed by comparing the 5G networks considering the advanced high gain beamforming features with small cells. Through the analysis, it was found (Chapter 6 first part) that the 5G network is capable of imposing higher EMF levels at the user end for both outdoor and indoor environments. However, the EMF level obtained from the 5G networks did not cross the current exposure guidelines set by the regulatory agencies for a larger area within the network but were found to be higher than the concurrent cellular networks. This elevated the necessity of a human EMF mitigation scheme to reduce the levels of exposure from the 5G downlink communications.

The second part of this thesis was the EMF mitigation protocols (Chapter 5) for both indoor and outdoor scenarios. Several technical points were investigated throughout this research for the purpose of human safety from cellular networks. While the mitigation protocol for the outdoor scenario is based on choosing alternative APs if the serving AP exceeds the EMF threshold, the mitigation schemes in the indoor environment rely on the reduction of resources like transmit power or antenna elements considering that there is no alternative AP to chose while the EMF level exceeds the threshold.

In the final part of this research work (Chapter 6), we pointed out the effectiveness of our proposed schemes for minimizing the human EMF exposure in terms of PD and SAR with the obtained results from simulations. The level of service (data rate) was chosen as the parameter for the trade-off for human safety in the proposed networks. However, all the proposed schemes were found to provide data rates within the 5G requirements that suggest the proposed protocols will keep the 5G network fully operational even at the worst possible case. We did not consider the effect of interference in this work as the main focus is to analyze the human EMF exposure which is not influenced by the interference level. We proposed a minimum separation distance between AP and UEs for a safe cellular network at the outdoor environment. Also, this research highlights the significance of considering SAR for the evaluation of human EMF exposure even at downlinks as SAR is a more effective metric than PD for measuring human safety. As possible future directions of this research, we suggest the following:

1. Considering a different metric other than PD or SAR as the parameter for EMF mitigation.

2. Investigate the human EMF exposure for uplinks for 5G cellular networks.

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