



# Downlink Electromagnetic Field Exposure Levels in Pre-5G and 5G Ultra-Dense Mobile Networks

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**Abstract.** 5G new radio (NR) is a new radio access network technology that will enable ultra-high speed, ultra-high reliability and ultra-low latency mobile services. The deployment of 5G NR is actively ongoing now in many regions worldwide. Nevertheless, the public is still concerned about the electromagnetic field (EMF) exposure from 5G networks due to the potential health risk. The goal of this research is to investigate the EMF exposure from downlink transmission of ultra-dense 5G mobile networks. In particular, both urban macro (UMa) cell and urban micro (UMi) cell scenarios are considered in this study. The EMF exposure level is simulated by using several standard path loss propagation models such as the free space model, 3GPP model, alpha-beta-gamma model and close-in reference model in both line-of-sight and non-line-of-sight scenarios. Then, the EMF exposure from 5G network is compared to that of the LTE network. Some results on the safe distance between 5G base station and the user equipment to minimize health risk are also presented.

**Keywords:** 5G · EMF exposure · path loss models · urban macro site · urban micro site

## 1 Introduction

5G new radio is the latest generation of mobile radio access technology that is based on some new technologies such as massive Multiple-Input-Multiple-Output (MIMO) and millimetre wave (mmWave) technology. The deployment of antenna array for massive MIMO in the 5G sites is expected to increase the number of antennas significantly compared to the previous generation of technologies [1]. Beamforming is another key technique that allows the antenna to control the directivity of the radiated power to the users. 5G signal transmission will also utilize new frequency spectrum in the millimetre wave (mmWave) bands rather than the lower radio frequencies that are being used currently in 4G networks. The mmWave frequency band provides ultra-wide bandwidth and may speed up the communication rate to 10 Gbps [2]. The adoption of small cell deployment approach is also inevitable in 5G mobile networks. These new wireless technologies and deployment strategy of 5G are causing growing concern regarding the

risk of higher EMF exposure to the users. This is mainly due to the capabilities of these new techniques in improving the received signal strength significantly.

2 Literature Review

2.1 EMF Exposure Limits

Permissible exposure limits for electromagnetic radiation have been established by standard organizations such as the International Commission for the Protection of Non-Ionizing Radiation (ICNIRP) and IEEE to ensure the safety of public and the mobile users [3, 13]. Power density (PD) and specific absorption rate (SAR) are two widely used metrics for checking exposure conformance. SAR refers to the amount of power absorbed by the human body or tissue. It is expressed in power level per unit mass. Another dosimetric quantity for exposure determination is PD which is a more straightforward measure. However, unlike SAR, it does not provide information on power absorption by the affected tissue. Table 1 and 2 show the recommended exposure limits from ICNIRP.

2.2 Related Works

In [2, 14], an analysis on EMF exposure for 5G networks is performed by using free-space path loss models and the result is compared to 4G and 3.9G in outdoor setting. Table 3 shows the simulation parameters considered in the study.

Table 1. Power Density (PD) Limits [3]

Exposure Characteristics	Frequency Range (MHz)	Power Density (W/m <sup>2</sup> )
Occupational workers	1–10	-
	10–400	10
	400–2,000	f/40
	2,000–300,000	50
General public	1–10	-
	10–400	2
	400–2,000	f/200
	2,000–300,000	10

Table 2. Specific Absorption Rate (SAR) Limits [3]

Exposure Characteristics	Average SAR (mW/kg)	Local SAR (10 g; ≥ 6 min) (W/kg)	
		Head & Trunk	Limbs
Occupational workers	400	10	20
General public	80	2	4

**Table 3.** System settings of 5G, 4G and 3.9G [2]

Parameter	Value		
	5G	4G	3.9G
Frequency	28 GHz	2 GHz	1.9 GHz
Bandwidth	850 MHz	20 MHz	20 MHz
Transmit power	35 dBm	49 dBm (UMa) and 44 dBm (UMi)	43 dBm
Number of antennas	8T8R	4	4
ISD	500 m (UMa) and 200 m (UMi)		3,000 m (UMa) and 1,000 m (UMi)
Antenna gain	8 dBi per element		17 dBi

A dense network deployment is assumed so as to determine the worst possible EMF exposure and to provide the best suggestion on human safety exposure [2, 14]. There are two scenarios considered, namely the Urban Macro (UMa) and Urban Micro (UMi). Random locations of users are assumed in a line-of-sight environment with 19 base stations having 3 sectors and 10 active user equipment (UE) per sector.

The result shows that 4G systems in UMa environment have the highest power density exposure followed by 5G, 3.9G and 4G system in UMi. The minimum safe distance required so that the exposure is below the limit is found to be around 3 m from the antenna. Meanwhile, 5G systems recorded the highest SAR exposure followed by 4G in UMa, 3.9G and 4G systems in UMi environment. The minimum safe distance needed is around 6 m.

Most of the existing works concerning simulation-based EMF exposure evaluation for 5G networks employed the free-space path loss model. This is due to the requirement of understanding the worst case scenario for safety reason. Nevertheless, there are other realistic and more physically based radio propagation models which are useful for understanding the actual exposure in specific 5G network scenarios. In this work, some standard radio propagation models are used for investigating the PD and SAR exposure levels.

### 3 Methodology

This section outlines the system model for the ultra-dense 5G mobile networks. Path loss models adopted for analysis of EMF exposure are described. Received power in the downlink is calculated according to the path loss and system models. The 3GPP release 15 [4] is referred to and practical network parameter values from our industrial collaborator are used for developing and specifying the parameters of the system model.

### 3.1 System Models

EMF exposure is evaluated based on the parameters that impact the radio propagations as presented in Table 4, 5 and 6 for the LTE, 5G sub-6-GHz and 5G mmWave systems respectively [2, 4–7, 14]. The basis of the values used is also justified through comprehensive link budget analysis. An example is given in Appendix I.

Figure 1 illustrates the system-level setup for the simulation scenarios considered in this work.

### 3.2 Radio Propagation Models

#### 3.2.1 Free-Space Path Loss Model

The path loss model for free-space environment is given by [10]

$$PL_{FS} = 20 \log_{10}(f) + 20 \log_{10}(d) - 27.5 \quad (1)$$

**Table 4.** System Parameters for LTE Networks

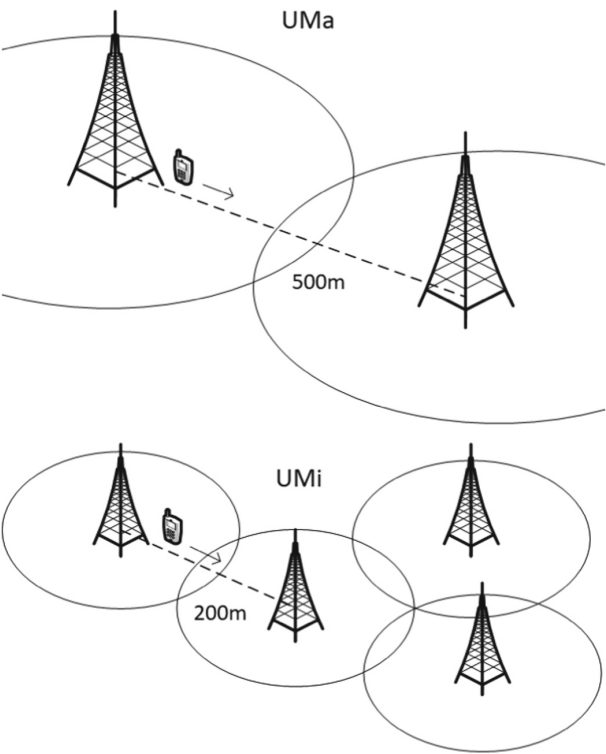
Parameter		LTE UMa	LTE UMi
Operating frequency	GHz	2	2
Inter-site distance	m	500	200
Bandwidth	MHz	20	20
Antenna Gain	dBi	12.02	12.02
Transmit power	dBm	49	44
Antenna Configuration	#	4	4
Antenna height	m	25	15

**Table 5.** System Parameters for 5G Sub-6-GHz Networks

Parameter		5G 3.5G 16T UMa	5G 3.5G 64T UMa	5G 3.5G 16T UMi	5G 3.5G 64T UMi
Operating frequency	GHz	3.5	3.5	3.5	3.5
Inter-site distance	m	500	500	200	200
Bandwidth	MHz	100	100	100	100
Antenna Gain	dBi	23	25	23	25
Transmit power	dBm	53.01	53.01	45	45
Antenna Configuration	#	16T16R	64T64R	16T16R	64T64R
Antenna height	m	25	25	15	15

**Table 6.** System Parameters for 5G mmWave Networks

Parameter		5G 28G 4T UMa	5G 28G 8T UMa	5G 28G 4T UMi	5G 28G 8T UMi
Operating frequency	GHz	28	28	28	28
Inter-site distance	m	500	500	200	200
Bandwidth	MHz	800	850	800	850
Antenna Gain	dBi	24.06	26	24.06	26
Transmit power	dBm	35	35	33	33
Antenna Configuration	#	4T4R	8T8R	4T4R	8T8R
Antenna height	m	25	25	15	15



**Fig. 1.** System-level setup of the simulation scenarios

where  $f$  is the operating frequency in MHz and  $d$  is the distance from user to the antenna in meters.

### 3.2.2 3GPP Path Loss Model

For UMa-LoS scenarios, the path loss model specified by 3GPP is given by [4]

$$PL_{UMa-LoS} = \begin{cases} PL_1 & 10m \leq d_{2D} \leq d'_{BP} \\ PL_2 & d'_{BP} \leq d_{2D} \leq 5km \end{cases} \quad (2)$$

where

$$PL_1 = -27.55 + 20 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \quad (3)$$

$$PL_2 = -27.55 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - 10 \log_{10}((d'_{BP})^2 + (h_{BS} - h_{UE})^2) \quad (4)$$

On the other hand, for UMi-LoS scenarios,

$$PL_{UMi-LoS} = \begin{cases} PL_1 & 10m \leq d_{2D} \leq d'_{BP} \\ PL_2 & d'_{BP} \leq d_{2D} \leq 5km \end{cases} \quad (5)$$

where

$$PL_1 = -27.55 + 21 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \quad (6)$$

$$PL_2 = -27.55 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - 9.5 \log_{10}((d'_{BP})^2 + (h_{BS} - h_{UE})^2) \quad (7)$$

For UMa-NLoS and UMi-NLoS, the path loss models are given by (8) and (9) respectively as follows

$$PL_{UMa-NLoS} = 13.54 + 39.08 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - 0.6(h_{UE} - 1.5) \quad (8)$$

$$PL_{UMi-NLoS} = 35.3 \log_{10}(d_{3D}) + 22.4 + 21.3 \log_{10}(f_c) - 0.3(h_{UE} - 1.5) \quad (9)$$

where  $d_{3D}$  is the 3D distance from the user to the base station antenna in m,  $d_{BP}$  is the breakpoint distance in m which has been fixed to 50 m,  $f_c$  is the carrier frequency in MHz,  $h_{BS}$  is the height of antenna in m and  $h_{UE}$  is the user equipment height in m. The 2D distance (or distance on ground level) can be determined as

$$d_{2D} = \sqrt{(d_{3D})^2 - (h_{bs} - h_{ue})^2} \quad (10)$$

**Table 7.** ABG coefficients [11]

Network Scenario		$\alpha$	$\beta$	$\gamma$
UMa	LoS	2.8	11.4	2.3
	NLoS	3.3	17.6	2.0
UMi	LoS	2.0	31.4	2.1
	NLoS	3.5	24.4	1.9

**Table 8.** Path loss exponent in CI model [11]

Network Scenario		$n$
UMa	LoS	2.0
	NLoS	2.7
UMi	LoS	2.0
	NLoS	3.1

### 3.2.3 Alpha-Beta-Gamma (ABG) Path Loss Model

The ABG can be expressed as [11]

$$PL_{ABG} = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f) \quad (11)$$

where  $\alpha$  and  $\gamma$  are path loss coefficients that rely on distance and frequency and  $\beta$  denotes the offset value for path loss in dB. Distance between the user and antenna in m is represented by  $d$  and  $f$  is the carrier frequency in GHz. The values of ABG model's coefficients are summarized in Table 7.

### 3.2.4 Close-In (CI) Reference Path Loss Model

For the CI model with reference distance of 1m, the path loss expression is given by [11]

$$PL_{CI} = PL_{FS(d=1m)} + 10n \log_{10}(d) \quad (12)$$

where  $PL_{FS(d=1m)}$  is the free-space path loss at the reference distance of 1 m,  $n$  is the path loss exponent as presented in Table 8 and  $d$  is the distance between antenna and user in m.

## 4 Results and Discussion

In this section, results and analysis on EMF exposure for pre-5G and 5G systems are presented based on the four different propagation models described in the previous section for both LoS and NLoS scenarios. Two exposure metrics are considered, namely

the power density (PD) and specific absorption rate (SAR). Based on ICNIRP recommendation, the general public exposure limit is  $10 \text{ W/m}^2$  for PD and  $2 \text{ W/kg}$  for SAR.

Power density in free-space with the unit of watt per square meter ( $\text{W/m}^2$ ) can be expressed as [9]:

$$PD = P_T G_T / 4\pi d^2 = EIRP / 4\pi d^2 \quad (13)$$

where  $P_T$  is the transmitted power,  $G_T$  is the transmit antenna isotropic gain and  $d$  is distance of user from the transmit antenna. For non-free-space radio propagation, the PD will be further attenuated by the path loss according to the specific propagation model considered.

SAR exposure, on the other hand, can be expressed at the air-boundary as follows:

$$SAR = 2PD(1 - R^2) / \delta \rho \quad (14)$$

where  $(1 - R^2)$  is the power absorption coefficient [8] [9, 12],  $\delta$  is the skin penetration depth of 1 mm and  $1 \text{ g/cm}^3$  of mass density  $\rho$  is assumed [2].

#### 4.1 Free-Space Path Loss Model

Figure 2 and Fig. 3 depict the EMF exposure in terms of PD and SAR respectively based on the free space path loss propagation model.

Figure 2 shows the 3.5 GHz 64T 5G system in UMa produced the highest PD and SAR. This is because the transmitted power and antenna gain are higher compared to

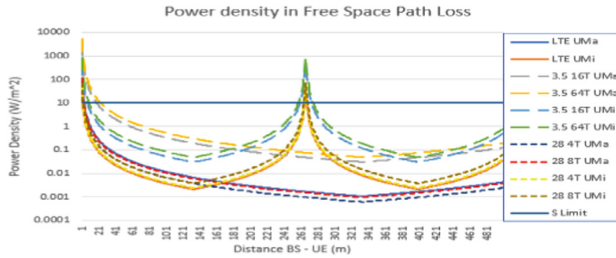


Fig. 2. PD versus distance for free space path loss model

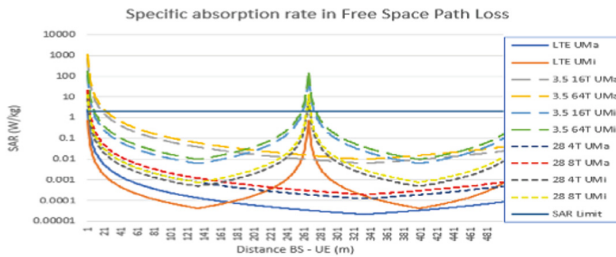


Fig. 3. SAR versus distance for free space path loss model



that of other networks. Minimum safe distance of 24 m must be maintained between the user and the base station antenna to keep the exposure below the limits specified for PD and SAR. In contrast, 28 GHz 5G systems in UMa and UMi and the LTE networks only require a minimum safe distance of about 3 m.

## 4.2 3GPP Path Loss Model

### 4.2.1 Line-of-Sight

The 3GPP model uses two equations that are dependent on the breakpoint distance. It can be observed from Fig. 4 and Fig. 5, when the ground level distance from user to the base station antenna reaches 50 m, the path loss becomes higher and results in lower received power. Therefore, lower exposure level is observed beyond the breakpoint distance. For distance below the breakpoint, free space path loss propagation model is used. Based on the results, the safe distance required is found to be about 24 m.

### 4.2.2 Non-Line-of-Sight

For NLoS environment, path loss is higher and hence received power is lower. As shown in Fig. 6, the 3.5 GHz 64T 5G network exhibits the highest exposure level. Since SAR is PD dependent, therefore, higher PD results in higher SAR as shown in Fig. 7. For this NLoS scenario, the safe distance required is found to be about 3 m.

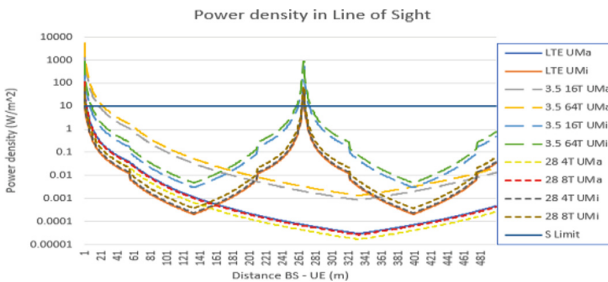


Fig. 4. PD versus distance for LoS 3GPP path loss model

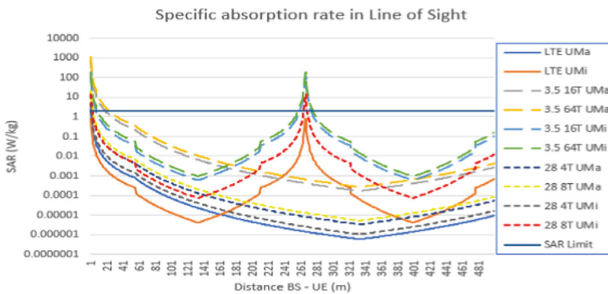


Fig. 5. SAR versus distance for NLoS 3GPP path loss model

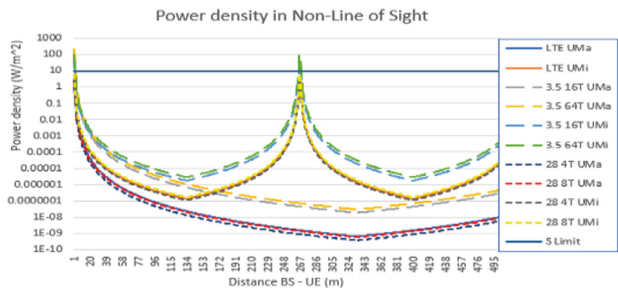


Fig. 6. PD versus distance for NLoS 3GPP path loss model

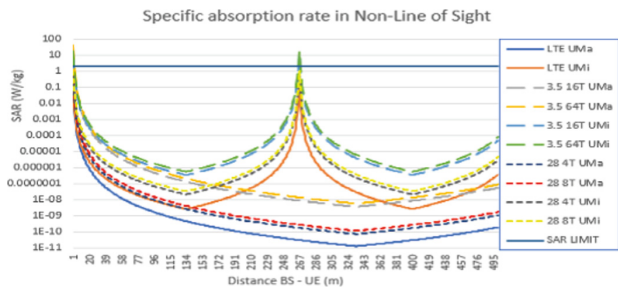


Fig. 7. SAR versus distance for NLoS 3GPP path loss model

4.3 ABG Path Loss Model

4.3.1 Line-of-Sight

As shown in Fig. 8, the 3.5 GHz 64T 5G system for UMa has the highest level of PD. However, due to the smaller inter-site distance (ISD) of the UMi (i.e., 200 m), the PD of the 3.5 GHz 5G UMi cell is higher than that of the UMa cell near the UMa cell edge. For the results of SAR in Fig. 9, the 3.5 GHz 64T 5G system in UMa gives the highest level of SAR. The LTE and 28 GHz 5G networks show the lowest SAR. It is found base station antenna must be at least 47 m or further away from the users to ensure both PD and SAR are below the safety limits.

4.3.2 Non-line-of-Sight

For NLoS scenario, the PD versus distance for ABG path loss propagation model is presented in Fig. 10. The PD level as per the ABG propagation model in NLoS is lower than that of the same model in LoS scenario. This is because of the higher path loss due to the absent of direct path signal. Figure 11 compares the SAR of 5G and LTE networks. The higher PD of the 3.5 GHz 5G systems results in the higher SAR level compared to the 28 GHz 5G and LTE networks. The minimum distance between the base station antenna and user should be at least 19 m or more to prevent the EMF exposure exceeding the limit.



Fig. 8. PD versus distance for LoS ABG path loss model

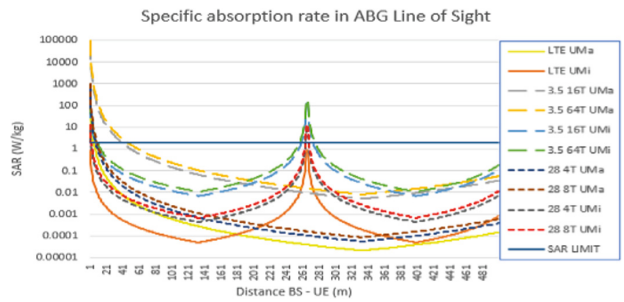


Fig. 9. SAR versus distance for LoS ABG path loss model

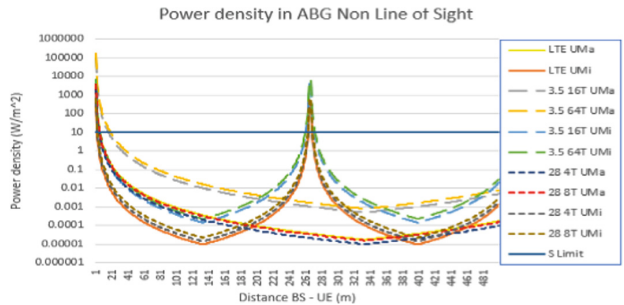
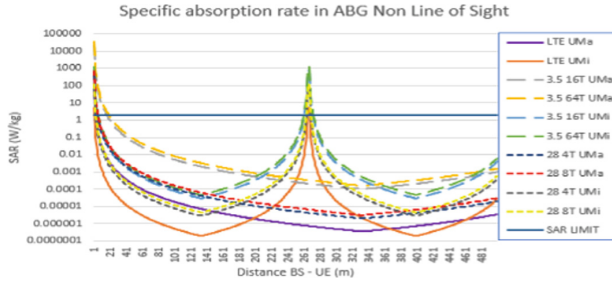


Fig. 10. PD versus distance for NLoS ABG path loss model

## 4.4 CI Reference Path Loss Model

### 4.4.1 Line-of-Sight

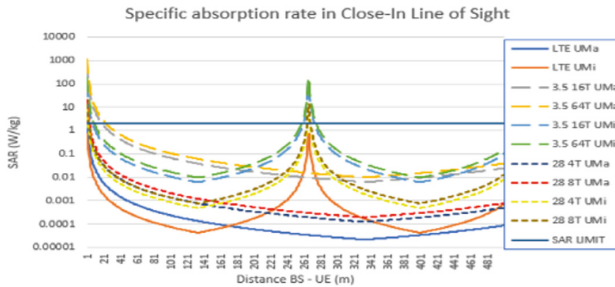
PD and SAR based on CI reference propagation model against the distance of UE from the BS are presented in Fig. 12 and Fig. 13 respectively. It can be observed that the 3.5 GHz 64T 5G system in UMa has the highest level of EMF exposure in terms of PD and SAR. LTE and 28 GHz 5G networks have relatively lower EMF radiation level. The minimum safe distance as per the CI reference propagation model for the 5G systems should be at least 24 m considering both the PD and SAR limits.



**Fig. 11.** SAR versus distance for NLoS ABG path loss model



**Fig. 12.** PD versus distance for LoS CI reference path loss model



**Fig. 13.** SAR versus distance for LoS CI reference path loss model

#### 4.4.2 Non-Line-of-Sight

For NLoS environment, it can be observed from Fig. 14 and Fig. 15, the highest EMF exposure is from the 3.5 GHz 64T 5G system. The minimum safe distance considering both PD and SAR limits using CI reference NLoS propagation model is about 11 m.

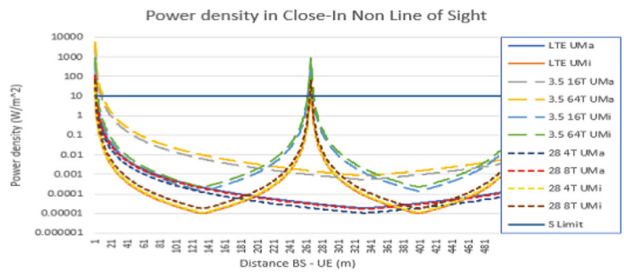


Fig. 14. PD versus distance for NLoS CI reference path loss model

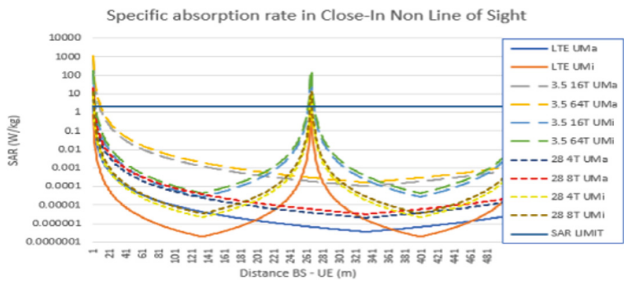


Fig. 15. SAR versus distance for NLoS CI reference path loss model

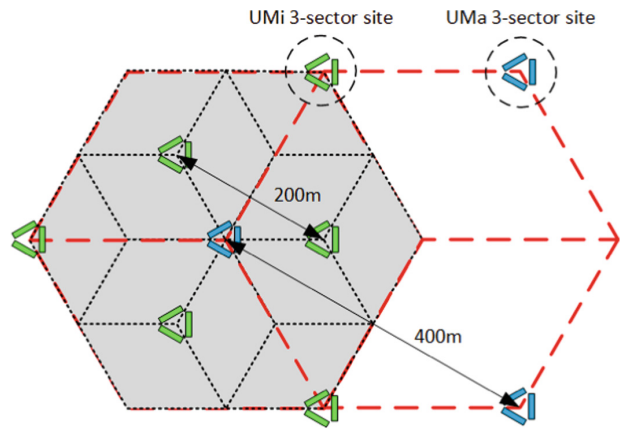


Fig. 16. Deployment scenario of 3-sector UMi sites

### 4.5 Impact of 5G Network Deployment

To understand the impact of network migration from LTE to 5G on EMF radiation exposure, a network deployment scenario considering 3-sector UMa and UMi sites is investigated (see Fig. 16). The study area is indicated as the shaded region in Fig. 16.

**Table 9.** Network migration scenarios and their impact on the change of PD ( $\text{W}/\text{m}^2$ ) and SAR ( $\text{W}/\text{kg}$ )

Network Migration	Free-space		CI reference (NLoS)	
	% Area with $+\Delta PD$ ( $+\Delta SAR$ )	Average $\Delta PD$ ( $\Delta SAR$ )	% Area with $+\Delta PD$ ( $+\Delta SAR$ )	Average $\Delta PD$ ( $\Delta SAR$ )
LTE UMa $\rightarrow$ 3.5 GHz 64T 5G UMa	100% (100%)	+0.68 (+0.68)	100% (100%)	+55.5m (+55.7m)
LTE UMa $\rightarrow$ 3.5 GHz 64T 5G UMi	97% (97%)	+0.33 (+0.33)	89% (90%)	+8.4m (+8.6m)
LTE UMi $\rightarrow$ 3.5 GHz 64T 5G UMi	100% (100%)	+0.33 (+0.33)	100% (100%)	+9.1m (+9.2m)
LTE UMa $\rightarrow$ 28 GHz 8T 5G UMa	0% (100%)	-0.1m (+2.7m)	0% (100%)	-0.01m (+0.2m)
LTE UMa $\rightarrow$ 28 GHz 8T 5G UMi	80% (83%)	+13m (+15.8m)	41% (48%)	-0.4m (-0.2m)
LTE UMi $\rightarrow$ 28 GHz 8T 5G UMi	100% (100%)	+13m (+16.1m)	100% (100%)	+0.4m (+0.5m)

Six different network migration strategies are considered in the simulation as shown in Table 9. The free-space propagation model is considered for the worst case scenario, while the CI reference (NLoS) model is assumed for a more realistic dense urban scenario.

The results show migrating from LTE UMa to 3.5 GHz 64T 5G UMa gives the largest impact on increasing the average PD and SAR within the study area. This is mainly due to the higher transmit power and antenna gain of the 5G system. In all cases, almost the entire study area experiences increase of exposure level except for the case of migrating from LTE UMa to 28 GHz 8T 5G UMa. For the NLoS scenarios, the changes in the exposure levels are relatively less significant compared to those of the free-space (worst case) scenarios.

## 5 Conclusion

In summary, the EMF exposure levels of both sub-6 GHz and 28 GHz 5G networks in terms of PD and SAR are below the recommended exposure limits. This is true for the area that is accessible by the users considering both the worst case (i.e., free-space) scenarios and the more physically based radio propagation scenarios. The 3.5 GHz 64T 5G network considered in this study shows the highest exposure level compared to the LTE and 28 GHz 5G networks. In contrast, the 28 GHz 5G network has slightly lower

PD exposure compared to LTE network in UMa while LTE in UMi has the lowest PD level. Moreover, LTE network in UMa and UMi has the lowest SAR exposure compared to 5G networks. The investigation on the impact of EMF exposure when migrating from LTE to 5G system shows migrating from LTE UMa to 3.5 GHz 64T 5G UMa results in the most significant increase in the average PD and SAR within the study area. This is mainly due to the higher transmit power and antenna gain of the 5G base station. For future work, massive MIMO beamforming and more detailed antenna radiation pattern can be considered in the exposure evaluation.

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# Appendix I

Example of link budget analysis for 5G NR at 3.5 GHz for verification of the simulation parameter settings:

		DU			
Link Budget - PDSCH		NR 3.5G 16T SA	NR 3.5G 64T SA	NR 3.5G 16T SA	NR 3.5G 64T SA
Data Rate	Mbps	50.00	50.00	100.00	100.00
Carrier Frequency	GHz	3.50	3.50	3.50	3.50
Channel Bandwidth	MHz	100.00	100.00	100.00	100.00
Subcarrier Space	kHz	30.00	30.00	30.00	30.00
Downlink Ratio		64.29%	64.29%	64.29%	64.29%
Total RB Number	#	273	273	273	273
eNodeB/gNodeB Antenna Configuration		16T16R	64T64R	16T16R	64T64R
UE Antenna Configuration	#	2T4R	2T4R	2T4R	2T4R
Used resource blocks	#	240	240	261	261
MCS Index	#	8	8	14	14
Modulation Order		2	2	4	4
TBSize	#	40778	40778	81556	81556
Tx					
eNodeB/gNodeB Tx Power	dBm	53.01	53.01	45.00	45.00
eNodeB/gNodeB Antenna Gain	dBi	23.00	25.00	23.00	25.00
Cable Loss	dB	0.00	0.00	0.00	0.00
Tx EIRP	dBm	76.01	78.01	68.00	70.00
Rx					
Thermal Noise Density	dBm/Hz	-174.00	-174.00	-174.00	-174.00
UE Noise Figure	dB	7.00	7.00	7.00	7.00
Required SINR	dB	-1.32	-1.32	3.62	3.62
UE Sensitivity	dBm	-88.95	-88.95	-83.65	-83.65
UE Antenna Gain	dBi	0.00	0.00	0.00	0.00
DL Interference Margin	dB	7.00	6.00	11.00	10.00
Body Loss	dB	0.00	0.00	0.00	0.00
Environment (3GPP)					
Cell Area Coverage Probability	%	95.00	95.00	95.00	95.00
Penetration Loss	dB	26.00	26.00	26.00	26.00
Std Dev of Slow Fading	dB	10.00	10.00	10.00	10.00
Shadow Fading Margin	dB	11.24	11.24	11.24	11.24
Hand off Gain	dB	4.49	4.49	4.49	4.49
MAPL	dB	125.21	128.21	107.90	110.90
Radius(3GPP_NLOS)	m	308	368	109	131
ISD	m	462	552	163	196
eNodeB/gNodeB Antenna Height	m	25.00	25.00	25.00	25.00
UE Height (hUT)	m	1.50	1.50	1.50	1.50
Street Width_W	m	15.00	15.00	15.00	15.00
Building Height_h	m	25.00	25.00	25.00	25.00
Frequency Propagation Factor	#	20.00	20.00	20.00	20.00

## References

1. L. Chiaraviglio, A. S. Cacciapuoti, G. Di Martino, M. Fiore, M. Montesano, D. Trucchi and N. B. Melazzi, "Planning 5G networks under EMF constraints: State of the art and vision," *IEEE Access*, vol. 6, pp. 51021-51037, 2018.
2. I. Nasim, "Analysis of Human EMF Exposure in 5G Cellular Systems," M. S. Thesis, 2019.
3. International Commission for the Protection of Non-Ionizing Radiation (ICNIRP), "Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 74, pp. 494-522, 1998
4. 3GPP TSG RAN, "NR: Base Station (BS) radio transmission and reception. (Release 15)," 3GPP TS 38.104 V15.10.0, Jun. 2020.
5. 3GPP TSG RAN, "Study on channel model for frequencies from 0.5 to 100 GHz (Release 15)", 3GPP TR 38.901 V15.1.0, Sep. 2019
6. 3GPP TSG RAN, "Study on 3D channel model for LTE (Release 12)", 3GPP TR 36.873 V12.7.0, Dec. 2017
7. 3GPP TSG RAN, "Spatial channel model for multiple input multi output (MIMO) simulations (Release 9)", 3GPP TR 25.996 V9.0.0, Dec. 2009
8. T. Wu, T. S. Rappaport and C. S. Collins, "Safe for generations to come: Considerations of safety for millimeter waves in wireless communications," *IEEE microwave magazine*, vol. 16, no. 2, pp. 65-84, 2015.
9. S. I. Naqvi, N. Hussain, A. Iqbal, M. Rahman, M. Forsat, S. S. Mirjavadi and Y. Amin, "Integrated LTE and Millimeter-Wave 5G MIMO Antenna System for 4G/5G Wireless Terminals," *Sensors*, vol. 20, no. 14, p. 3926, 2020..
10. P. Shamanna, "Simple Link Budget Estimation and Performance Measurements of Microchip Sub-GHz Radio Modules," *Microchip*, AN1631, 2013.
11. S. Sun, T. S. Rappaport, S. Rangan, T. A. Thomas, A. Ghosh, I. Z. Kovacs, I. Rodriguez, O. Koymen, A. Partyka and J. Jarvelainen, "Propagation path loss models for 5G urban micro- and macro-cellular scenarios," in 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), 2016.
12. O. P. Gandhi and A. Riaz, "Absorption of Millimeter Waves by Human Beings and its Biological Implications," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 34, no. 2, pp. 228-235, Feb 1986, doi: <https://doi.org/10.1109/TMTT.1986.1133316>.
13. K. R. Foster, S. Kodera, and A. Hirata, "5G communication systems and radiofrequency exposure limits," *IEEE Future Networks Tech Focus*, vol. 3, no. 2, 2019.
14. S. Kim and I. Nasim, "Human Electromagnetic Field Exposure in 5G at 28 GHz," in *IEEE Consumer Electronics Magazine*, vol. 9, no. 6, pp. 41-48, 1 Nov. 2020, doi: <https://doi.org/10.1109/MCE.2019.2956223>.



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