International Journal of Modern Research in Engineering and Technology (IJMRET)
www.ijmret.org Volume 9 Issue 7 ǁ July 2024.

Investigating Electromagnetic Radiation Within People in Crowds: A Case Study of SAR, Electrical Field, Skin Depth And ERP

Aissa Babaaddoun[1], Saban Selim Seker[1]
[1](Electrical and Electronics Engineering Department, Uskudar University, Turkey)

ABSTRACT: *This ground-breaking research investigates the behavior of electromagnetic (EM) waves in densely populated environments using a Multicomponent Discrete Propagation Model (MCDM). Our analysis focuses on four critical parameters: Specific Absorption Rate (SAR), Electrical Field, Skin Depth, and Effective Radiated Power (ERP) by working on crowd densities and frequencies relevant to 2G, 3G, 4G, and 5G technologies, the research directly addresses real-world exposure scenarios. Notably, this study is the first to employ a Multicomponent Discrete Propagation Model for such an analysis, offering a novel approach to understanding wave behavior in crowded spaces. Through comprehensive simulations, we explore how variations in electrical field strengths impact SAR, skin depth, and ERP. The obtained results are meticulously compared to established safety limits for whole-body SAR exposure (0.08 W/kg), providing valuable insights for developing safe radiofrequency (RF) exposure guidelines. Furthermore, this research extends beyond safety assessments. It aims to contribute to the design of future electronic devices that minimize overall RF emissions or target energy absorption in the human body. This innovative approach has the potential to significantly improve public confidence in the safety of wireless technologies.*

KEYWORDS *– ELECTROMAGNETIC, MCDM , Discrete Model, RF, SAR, Electrical Field, Skin Depth, ERP*

I. INTRODUCTION

Science's inherent fascination often leads to speculation about how scientific theories and their applications can be used to fulfill human desires. Telecommunication technology permeates our lives, especially in cities. We understand how weather and geography affect electromagnetic waves, but the impact of human crowds on these waves remains largely unexplored. Existing research focuses on biological effects and object interaction, neglecting how crowds might influence wave propagation through attenuation, absorption, scattering, or other mechanisms.

For a total coverage of network, telecommunication base stations are installed everywhere to assure the best performance of coverage, such stations are installed under standards of radiation required by the International Non-Ionizing Radiation Protection (ICNIRP) committee [1].

Standards set by both (ICNIRP) and the IEEE Standards Association (IEEE C95.1, 2019) establish limits for Whole Body Specific Absorption Rate (WBSAR) emitted by mobile phones and base stations. These limits ensure safe exposure levels. The maximum allowable WBSAR is 0.08 watts per kilogram averaged over the entire body, and the maximum localized Specific Absorption Rate averaged over any 10 grams of tissue should not exceed 2 watts per kilogram (W/kg).

In this study, we are going to implement Multicomponent Discrete Propagation Model developed in the paper [2] for a sake to to analyze the behavior of electromagnetic waves in human crowded environments. The study will focus on four key parameters: Specific Absorption Rate (SAR), Electrical Field, Skin Depth, and Effective Radiated Power.

II. DISCRETE MODEL BACKGROUND

A 1994 paper by S.S. Şeker (revised in 1995) introduces a novel radio frequency (RF) propagation model specifically designed for forests [2]. This model treats forests as collections of individual scatterers (trees and leaves) with real-world biophysical data. This approach provides more accurate predictions of signal attenuation compared to models using a single, averaged property for the forest canopy. Studies suggest that as radio waves travel deeper into forests, unpredictable wave behavior (incoherent) becomes more dominant.

EM fields themselves can be categorized into two parts: the predictable component (coherent) and the unpredictable, random component (incoherent). Different theoretical methods are needed to analyze each type of the field. The model assumes that the forest is made up of identical scatterers, each with a specific volume (V_p), a material property called relative dielectric constant (ε_r), and a radius (R).

The electrical field equation of scattering components can be represented as:

$$E_{pp} = exp\ (iK_{pp}L) \quad \wedge \quad p \in \{h, v\} \qquad (1)$$

Where, the effective propagation equation is given by

$$K_{pp} = k_0 + \frac{2\pi}{k_0}\{\rho_t f_{pp}^{(t)} \rho_b f_{pp}^{(b)} \rho_n f_{pp}^{(n)} \rho_l f_{pp}^{(l)} \qquad (2)$$

denoting that $f_{pp}^{(t)}$, $f_{pp}^{(b)}$, $f_{pp}^{(n)}$ *and* $f_{pp}^{(l)}$ are the average forward scattering amplitudes for trunks, branches, needles, and leaves, respectively.

Where $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$ the free space propagation constant, and L is the effective path length travelled by the wave.

The radio wave propagation through a forest can be seen as two channels working together, a coherent channel and an incoherent channel. The antenna initially transmits a well-defined wave (coherent wave). However, as this wave travels through the forest, it weakens due to two factors: absorption by the trees (ohmic losses) and scattering by the trees, which creates a new wave with random ups and downs (incoherent wave). The term (($\omega = \omega_1 = \omega_2$) helps us determine which of these two channels (coherent or incoherent) plays a dominant role in forest propagation for a specific frequency (ω). For detailed coherent and incoherent equations, can be referred to the reference [4].

Characterizing vegetation involves three key levels: Electrical Properties, Forest Geometry and Canopy. Electrical properties is where the green wood and leaves (high water content) share a similar relative permittivity (ε_r), a measure of interaction with electric fields. Forest geometry defined by density, size, and orientation which are key parameters for trunks, branches, and leaves. Canopy is a dense layer of branches and leaves supported by the trunks.

Beyond electrical properties, the physical characteristics of trees, including size, shape, and orientation, significantly influence wave propagation. Tree trunks, being the largest scatterers in a forest, receive the most detailed characterization. Notably, in uniform forests like homogeneous stands or plantations, the diameter distribution of these trunks is dependent on a normal (Gaussian) distribution.

III. Transformation

3.1 Initiation

Trees, despite biological differences, offer a model to understand human impact on radio waves due to their similar shapes and influence on wave propagation. A simplified analogy (tree trunk = body, branches = limbs, leaves = extremities) highlights this, but requires addressing size/age variations in trees (e.g., mass/density conversion). Research neglects interaction of radio waves with large crowds. Studying this gap could lead to improved wireless and potentially new applications.

3.2 Hypothesis

Combining Gabriel's human tissue data [3] with Şeker's vegetation model [2] allows us to study how electromagnetic waves interact with crowds. Human bodies, like vegetation, scatter and absorb waves due to varying permittivity. This suggests humans and trees might behave similarly at large scales, making the vegetation model a valuable platform to understand crowd impact on wave propagation.

3.3 Adjustment

The human-vegetation analogy is helpful, but requires adjustments for body size and density compared to trees. Accordingly, since we are planning to simulate the human parameters, we modified the needles to fingers, leaves to palms, branches to arms, then trunks to bodies. Consequently, we made adjustment to the diameter (D), length and density ρ) while probability remained unchanged. Regarding the body parameters, the body data in Şeker's paper [4] is improved while we performed new calculation for arms, palms, and fingers with reference to [5] and [6]. Details are illustrated in Simulation part.

IV. THEORITICAL ASPECTS

4.1 Specific Absorption Rate

Specific Absorption Rate (SAR) measures electromagnetic wave energy absorbed by human tissues (W/kg). It can be averaged over the whole body (WBSAR) or a smaller volume (1 gram or 10-gram average) [8]. SAR depends on the electric field strength within the body (modeled as a dielectric material) and is represented as follows [7]:

$$SAR = \frac{\sigma}{\rho}|E|^2 \quad \text{(W/kg)} \tag{3}$$

E is the electrical field in [V/m], σ represents the electrical conductivity in [S/m] and ρ denotes for the mass density in [Kg/m3]. These parameters depend on the properties of human tissues. According to reference [1] and IEEE Standards Association (IEEE C95.1-2019) with more illustration in [9], Whole Body SAR (WBSAR), for mobile phones and base stations, should not exceed the exposure limit, defined as 0.08 watts per kilogram and the maximum SAR value averaged over 10 grams of tissue is 2 watts per kilogram (W/kg).

4.2 Skin Depth

Skin depth (δ) is a depth penetration into human skin at which the amplitude of an electromagnetic wave has decayed to 1/e (approximately 37%) of its original value, and it is inversely proportional to the square root of the frequency (f) and conductivity (σ) of the material. This relationship can be expressed as :

$$\delta = \sqrt{\frac{1}{\sigma\pi\mu f}} \tag{4}$$

Where δ is Skin depth (meters), σ is Resistivity of the material (Ω·m), μ is Permeability of the material (H/m) (usually assumed to be the permeability of free space for most cases: $\mu_0 \approx 4\pi \times 10^{-7}$ H/m) and f is Frequency of the wave (Hz). From another perspective, skin depth (δ) can be expressed in terms of propagation constant:

$$\delta = \frac{1}{|\alpha|} \tag{5}$$

Where α (alpha) is attenuation constant (real part of the propagation constant K_{pp} of Equation 2) measured in reciprocal meters (1/m).

4.3 Effective Radiated Power (ERP)

Effective Radiated Power (ERP) is a theoritical concept used in radio frequency (RF) systems to quantify the total power an isotropic antenna would need to produce the same radiation intensity in the direction of the antenna's strongest beam. ERP and distance (R) determine the electric field strength (E) at a location. The Power density (S) near the antenna depends on transmitted power (Pt), gain (Gt), and distance (R) from antenna with a 1/R² relationship (inversely proportional to the square of the distance) .

$$S = \frac{P_t G_t}{4\pi R^2} \tag{6}$$

From Poynting's Theorem, we get an estimate of power density in terms of the E-field, where η0 is about 377 Ω or 120π Ω.

$$S = \frac{E^2}{2\eta_0} \tag{7}$$

The standard equation of Effective Radiated Power is :

$$ERP = P_t . G_t \tag{8}$$

Combining Equations 6, 7 and 8 we obtain :

$$E = \sqrt{\frac{ERP.60}{R^2}} \tag{9}$$

V. STUDY SCENARIO

This project simulates SAR in crowds exposed to 3G, 4G, and 5G frequencies. The program calculates SAR based on the electric field derived from the propagation constant. It also calculates skin depth and ERP across these bands. The core involves building scattering models using established data on human dielectric properties. The algorithm incorporates 13 elements representing obstacles within a crowd diameter, simulating wave attenuation and distortion. These elements combine to form a human model with four body types (Table 1) where the density for each of body, arms, palms and fingers are well calculated using references [4], [5] and [6] respectively.

Table 1: Input parameters for human model

Scattering components	D cm	Length cm	Probability	Density M3	Wh	Wv
Finger	1.80	5.98	0.103170	0.00076	0.47	0.73
Palm of child	6.35	7.50	0.250000	0.00014	0.06	0.06
Palm of woman	7.75	9.05	0.250000	0.00028	0.07	0.06
Palm of man	8.41	10.66	0.250000	0.00036	0.07	0.06
Palm type big	9.97	12.79	0.250000	0.00076	0.05	0.05
Arm of child	6.00	35.10	0.087500	0.00337	0.38	0.58
Arm of woman	8.90	47.00	0.287700	0.00828	0.47	0.73
Arm of man	9.00	54.00	0.310000	0.01069	0.46	0.74
Arm type big	10.50	60.5	0.316000	0.01588	0.45	0.62
Body of child	10.98	69	0.144000	0.02770	0.56	0.62
Body of woman	24.52	155.00	0.152000	0.04045	0.43	0.57
Body of man	30,89	177.00	0.384000	0.05076	0.50	0.63
Body type big	39,17	189.00	0.088000	0.06857	0.53	0.65

The program incorporates Equation (2) of the propagation constant K_{pp}. Utilizing this value, we will calculate Equation (1) E_{pp} , taking on consideration that:

$$E_{pp} = E_0 + E_1 \qquad (9)$$

Where E_{pp} is the attenuated (absorbed, scattered) electrical field, E_0 is the free space electrical field and E_1 is the distorted (or remaining) electrical field.

5.1 Preparing Crowd Density

To create a realistic crowd simulation, we first calculated the available space. The chosen 6-meter diameter translates to a circle with an area of approximately 28.27 square meters. This considers both the theoretical maximum occupancy and practical limitations.

People per square meter:

The available space (28.27 m²) represents the total area for the crowd. However, to estimate the number of people, we need to consider an average personal space required for comfortable standing, which can vary based on culture and preference [10]. Below is an image, as an example, that shows distribution of people within an area.

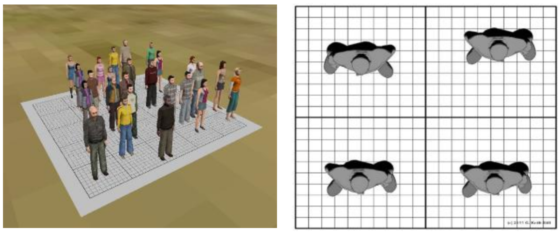

Figure 1: 1 person per square meter. Left and right images are created with one person in each square. The left image is 1 person per square meter but with random distribution (2 people in one square and 0 persons in the fourth). Crowds rarely pack regularly.

Considering personal space, the 28.27 m² area could hold roughly 71 people in a high-density scenario (0.4 m²/person) like a concert, or 36 people in a more comfortable setting (0.8 m²/person) as shown below respectively for figure 2 and figure 3.

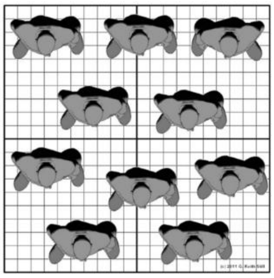

Figure 2: 2.5 people /m²

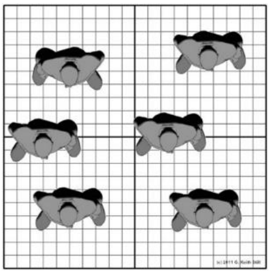

Figure 3:1.25 people /m²

While 36 people represent a comfortable crowd density, it's the limit for simulations due to diminishing changes in electrical field and SAR. Based on this fact, we prepared densities as shown below.

Table 2: Input parameters for crowd density

Input parameters: Crowd Density						
Scattering components	Number of people					
	2	4	8	12	22	36
	Density M3					
Finger	0.00038	0.00076	0.00152	0.00228	0.00418	0.00684
Palm of child	0	0.00014	0.00028	0.00042	0.00070	0.00126
Palm of woman	0.00028	0.00028	0.00056	0.00084	0.00168	0.00252
Palm of man	0.00036	0.00036	0.00072	0.00108	0.00216	0.00324
Palm type big	0	0.00076	0.00152	0.00228	0.00380	0.00684
Arm of child	0	0.00337	0.00674	0.01011	0.01685	0.03033
Arm of woman	0.00828	0.00828	0.01656	0.02484	0.04968	0.07452
Arm of man	0.01069	0.01069	0.02138	0.03207	0.06414	0.09621
Arm type big	0	0.01588	0.03176	0.04764	0.07940	0.14292
Body of child	0	0.02770	0.05540	0.08310	0.13850	0.24930
Body of woman	0.04045	0.04045	0.08090	0.12135	0.24270	0.36405
Body of man	0.05076	0.05076	0.10152	0.15228	0.30456	0.45684
Body type big	0	0.06857	0.13714	0.20571	0.34285	0.61713

VI. SIMULATION RESULTS

The simulations for Electrical Field, SAR, and Skin Depth were conducted at five distinct frequencies: 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, and 3500 MHz, while the ERP was performed under the frequencies 900 MHz, 1800 MHz, 2100 MHz and 5000 MHz.

6.1 Impact of 12-Person Model on Coherent and Incoherent Fields

In this section, we simulated a crowd scenario with a density of 12-people. The results are presented in separate graphs for each parameter (attenuated electrical field, skin depth, and SAR).

Each result shows both the coherent and incoherent components of the data, visualized for both vertical and horizontal polarizations.

Coherent Results

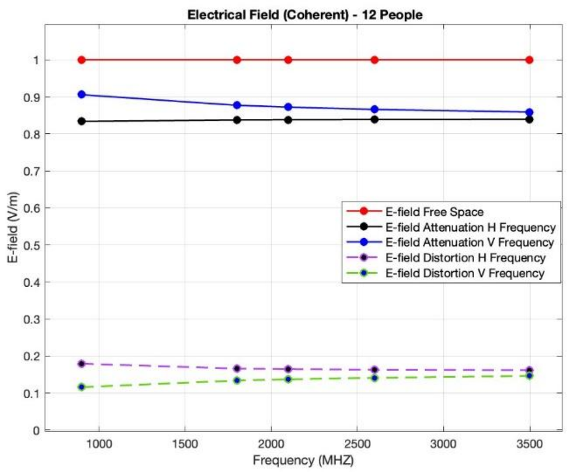

Figure 4: Coherent - Electrical Field Attenuation in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

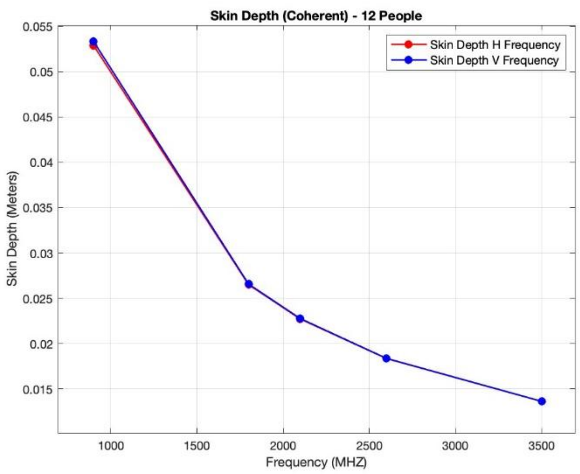

Figure 5: Coherent-Skin Depth in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600 and 3500 MHz

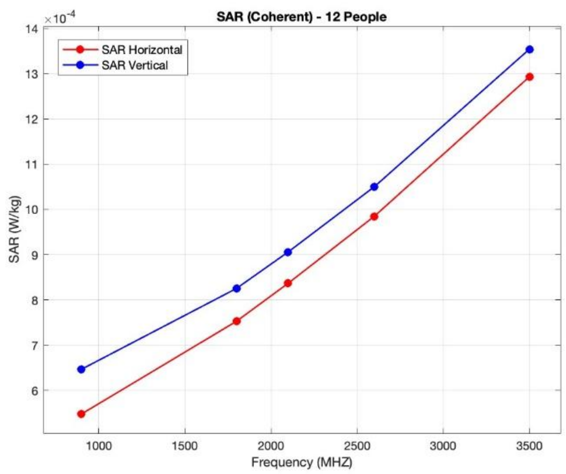

Figure 6-1: Coherent – SAR in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

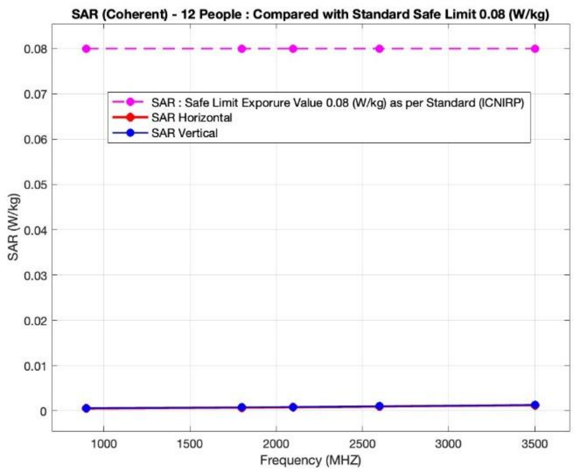

Figure 6-2: Coherent – SAR values compared with standard safe limit 0.08 (W/kg) in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

Incoherent Results

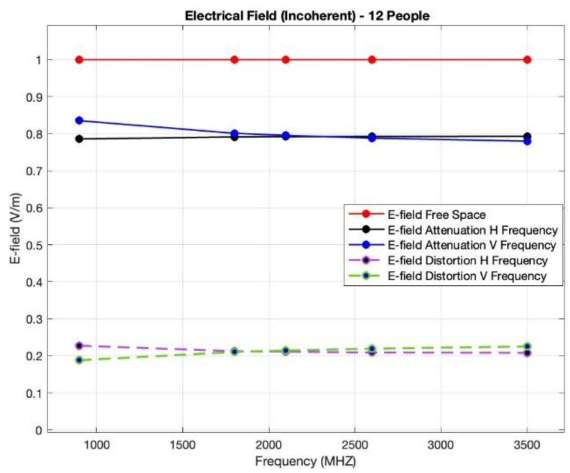

Figure 7: Incoherent - Electrical Field Attenuation in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

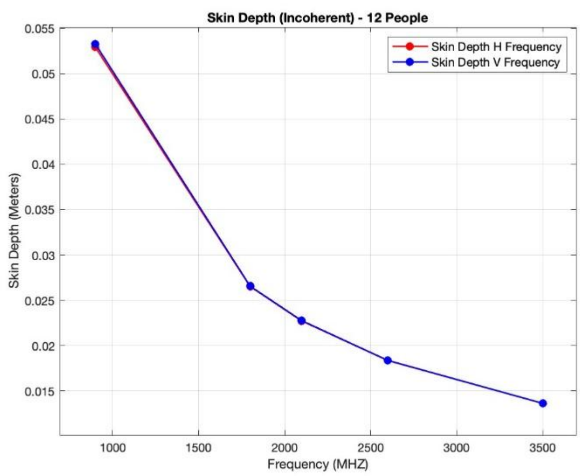

Figure 8: Incoherent - Skin Depth in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600 and 3500 MHz

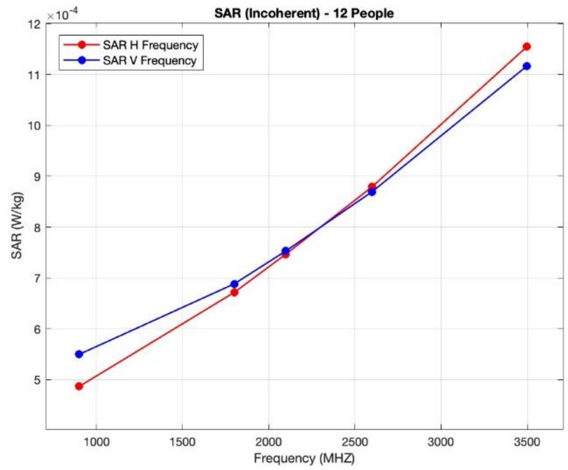

Figure 9-1: Incoherent – SAR in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

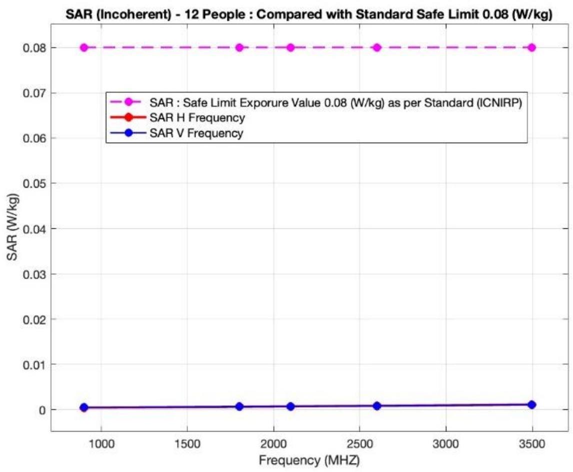

Figure 9-2: Incoherent – SAR values compared with standard safe limit 0.08 (W/kg) in a 12-People Crowd (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

6.2 Impact of Crowd Density on Electrical Field, SAR, and Skin Depth

In this section, we tend to simulate attenuated electrical field (absorbed), skin depth and specific absorption rate values against number of people. To simplify plotting the results, we focused on incoherent data of vertical frequencies.

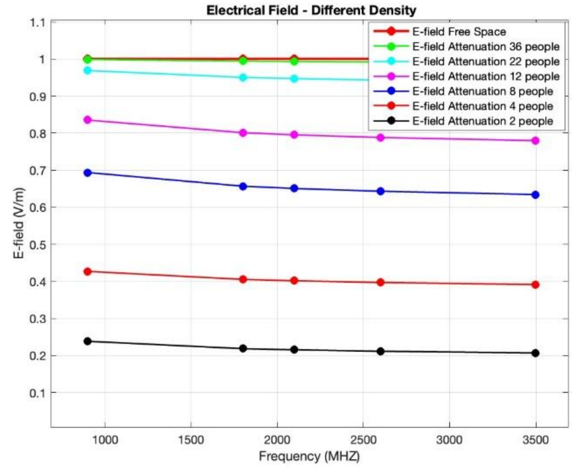

Figure 10: Electrical Field Attenuation in Crowds of Varying Density (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

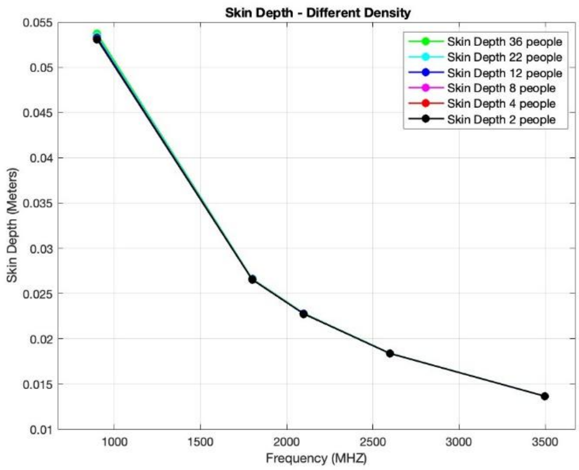

Figure 11: Skin Depth in Crowds of Varying Density (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

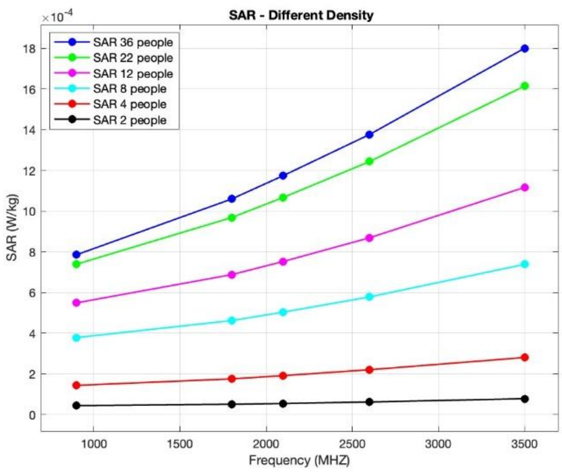

Figure 12-1: SAR in Crowds of Varying Density (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

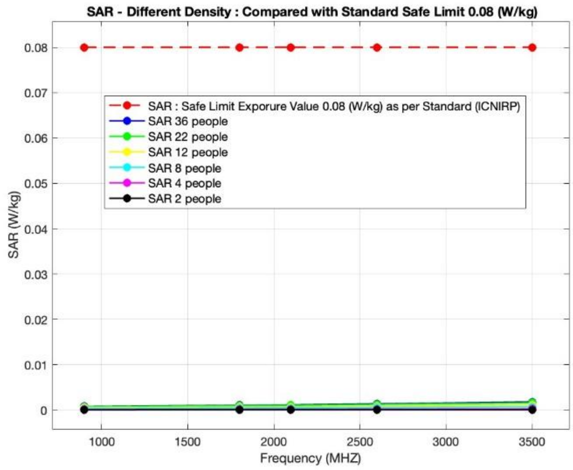

Figure 12-2: SAR values compared with standard safe limit 0.08 (W/kg) in Crowds of Varying Density (6m diameter) at 900, 1800, 2100, 2600, and 3500 MHz

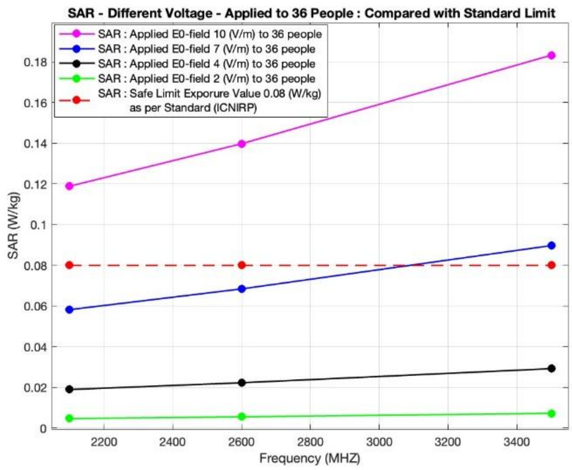

Figure 14: SAR values compared with standard safe limit 0.08 (W/kg) in a 36-People Crowd (6m diameter) at 2100, 2600, and 3500 MHz

6.3 Impact of Increased Electrical Field Strength

This section investigates the effects of increasing the electrical field strength on a 36-person model. We focus on two key parameters: Skin Depth and Specific Absorption Rate (SAR). Unlike previous sections, simulations were conducted only at three specific frequencies: 2100 Mhz, 2600 Mhz, and 3500 Mhz.

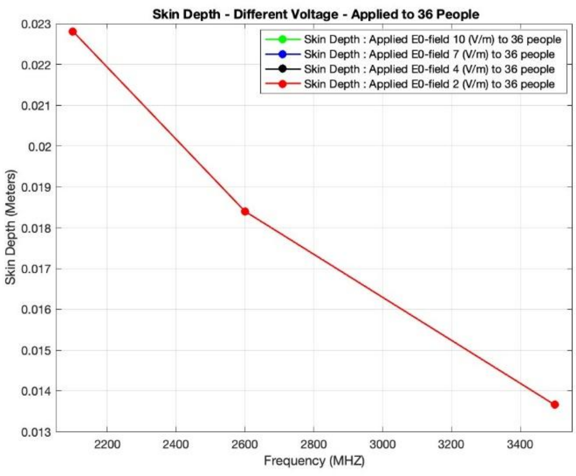

Figure 13: Skin Depth in a 36-People Crowd (6m diameter) at 2100, 2600, and 3500 MHz

6.4 Effective Radiated Power (ERP)

Effective radiated power (ERP) is calculated using Equation 8. We will also calculate the electrical field based on Equation 9 that is developed from power density and ERP equations.|
To proceed with these equations, we employed data from the base station's parameters illustrated below :

Table 3: The base station’s parameters

Radiation parameters	Frequency band			
	900 MHz	**1800 MHz**	**2100 MHz**	**5000 MHz**
Pt [W]	**500**	**250**	**250**	**501**
Gmax [dB]	**15.5**	**17.8**	**18.3**	**23.0**

To analyze the variation of the electrical field and Effective Radiated Power (ERP) with distance, we computed and simulated values across a range of distances from the antenna (R). The results is presented in two plots for better visualization: (R) 20-100 meters and (R) 1-20 meters as shown in Figure 15 and Figure 16 respectively.

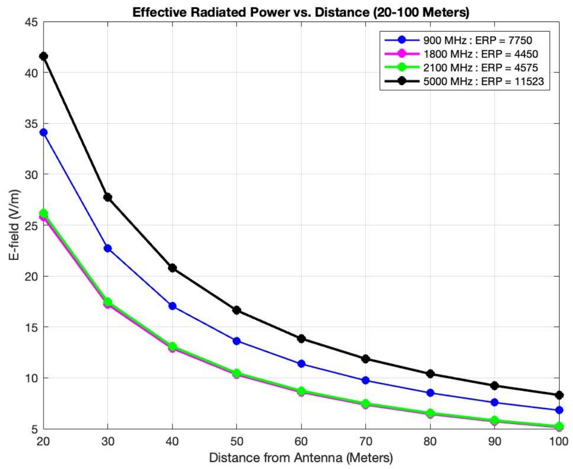

Figure 15: Effective Radiated Power Curves vs. Distance from Antenna (20-100 Meters)

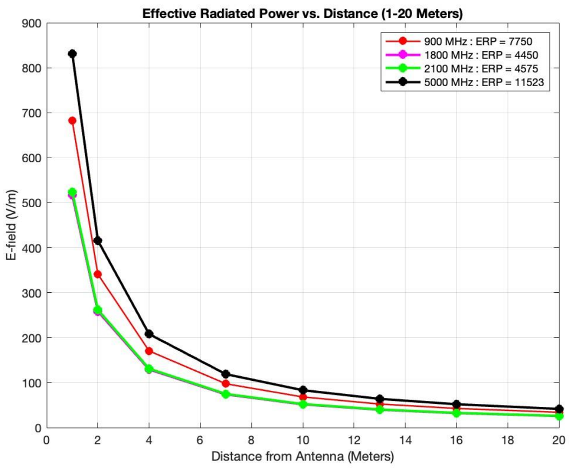

Figure 16: Effective Radiated Power Curves vs. Distance from Antenna (1-20 Meters)

VII. COMPARISON OF SAR ACROSS DIFFERENT LITERATURE

Across different literatures survey, it has been noticed that there is a luck of study for specifically SAR Whole Body. Following the completion of SAR calculations and simulations, we compared our results with existing literature [8]. Table 4 specifically focuses on this comparison for frequencies of 900 MHz and 1800 MHz.

SAR Whole body [W/Kg]	Frequency band					
	900 MHz			1800 MHz		
	Electrical field					
	4.50 [V/m]	4.70 [V/m]	5.10 [V/m]	4.60 [V/m]	5.15 [V/m]	6.20 [V/m]
SAR (Reference [8])	0.0120	0.0180	0.0150	0.0170	0.0200	0.0300
SAR (DiscreteModel)	0.0156	0.0171	0.0201	0.0226	0.0283	0.0411

Table 4: Comparison of SAR: Discrete Model vs Other Study (Frequencies: 900 MHz & 1800 MHz)

VIII. DISCUSION

The simulation results are interesting and found impressive to discuss.

8.1 Analysis of Coherent and Incoherent Fields (12- Person Model Influence)

Our simulations reveal minimal differences in behavior between coherent and incoherent electric fields, regardless of polarization (vertical/horizontal). Both experience attenuation and distortion (Figure 4). However, skin depth (Figure 5) shows a frequency-dependent decrease for all scenarios (coherent/incoherent, vertical/horizontal) with a peak around 900 MHz. This decrease is minimal between field types.

Furthermore, SAR (Specific Absorption Rate) exhibits a positive correlation with frequency (Figure 6) for both coherent and incoherent fields. Interestingly, in the coherent case, vertical polarization consistently shows higher SAR than horizontal. Conversely, incoherent fields see both polarizations initially increase but then switch roles around 2.3 GHz.

8.2 Varying Crowd Density Effects on Electrical Field, Skin Depth, and SAR

Simulations explored how crowd density affects electric field attenuation. We varied the number of people (2 to 36) within a fixed 6-meter diameter space. While frequency (900 MHz to 3500 MHz) slightly affected the electric field itself, higher crowd density led to increased attenuation, especially at 36 people (3500 MHz field reduced to 9.903 x 10^-1 V/m). Unlike the electric field, skin depth remained constant across densities but showed a frequency-dependent decrease (peak at 900 MHz).

Similarly, Specific Absorption Rate (SAR) increased with both higher crowd density and frequency (reaching a maximum of 0.001801 W/kg for the 36-person model at 3500 MHz). Importantly, all simulated SAR values remained well below the safety limit of 0.08 W/kg.

8.3 Impact of Increased Electrical Field Strength

Similar to previous observations, skin depth remained constant (around 2.28 x 10^-2 meters at 900 MHz) regardless of increasing electric field strength (2 V/m to 10 V/m) within a 36-person model (Figure 13). However, skin depth did decrease with frequency (as seen before).

In contrast, Specific Absorption Rate (SAR) in the 36-person model exhibited a direct increase with higher electric field strength. Importantly, the safe exposure limit (0.08 W/kg) was only exceeded for frequencies above 3500 MHz and a high field strength of 7 V/m (Figure 14).

8.4 Analysis of Effective Radiated Power

Simulations on Effective Radiated Power (ERP) vs distance from the antenna (R) revealed that field strength weakens with increasing distance, and for a frequency with specific transmitted power and gain, ERP remains constant across distances studied (1-100 meters). We also observed that frequency matters at short distances (<20 meters). For example, at lower frequencies (e.g., 900 MHz, 7750 Watt) reach a maximum of 34 V/m at 20 meters, while at medium frequencies (e.g., 1800 MHz at 4450 Watt) reach a maximum of 25 V/m at 20 meters but can reach 41 V/m at the same distance with higher ERP (11523 Watt).

On the other hand, remarked a dramatic electric field rise near antenna (<10 meters). The field intensity increases significantly for all frequencies and ERPs. At 2 meters, 900 MHz (7750 Watt) shows 341 V/m and 1800 MHz shows 258 V/m. This rise is even stronger for 5000 MHz (11523 Watt), reaching 415 V/m at 2 meters and 831 V/m at 1 meter.

8.5 Comparative Analysis: SAR values with existing literature

We compared calculated Specific Absorption Rates (SAR) with existing literature [8]. These studies measured SAR at specific locations near base stations with different distances.

In contrast, our study employed a discrete model method to calculate SAR, focusing on a single source of the electric field. This approach differs from the comparative studies that likely involved multiple sources in real-world environments.

Table 4 presents the comparison. As you can see, our SAR values (based on the discrete model) tends to be slightly higher. This difference might be attributed to the varying number of people considered in each scenario. For instance, the highest simulation SAR data we used represents a crowded environment with 36 people density. Conversely, the comparative studies obtained their results from laboratories or offices, which wouldn't typically have such a high density of people. Based on this analysis approach, the results are reasonable and acceptable.

IX. CONCLUSION

In conclusion, this research successfully employed a Discrete Model to analyze the behavior of electromagnetic waves in crowded environments with up to 36 people. The study focused on four key parameters: Specific Absorption Rate (SAR), Electrical Field, Skin Depth, and Effective Radiated Power (ERP). Notably, the type of electrical field (coherent or incoherent) and its polarization (vertical or horizontal) had minimal influence on the overall wave behavior.

Skin depth, representing the depth of wave penetration, consistently decreased with increasing wave frequency across all scenarios. Crowd density directly affected SAR, a measure of energy absorbed by the body. Higher densities resulted in increased SAR values, with minimal impact on skin depth. Importantly, simulations confirmed this effect even in crowded environments. For example, with a weak electric field (1 V/m), the maximum simulated SAR value (0.0018 W/kg) remained far below the safety limit (0.08 W/kg). However, it is crucial to note that SAR increases directly with increasing electrical field strength. While this study observed safe values at 1 V/m, a separate test with a stronger field (7 V/m) did show SAR exceeding the safety limit. This highlights the dependence of public SAR on field strength.

This study yielded the highest SAR values compared to others, likely due to higher crowd density used in the simulations. Additionally, the research successfully computed Effective Radiated Power (ERP), which is unique for each frequency band but it is dependent on transmitted power (Pt) and the gain (Gt).

The study also observed a distance-dependent decrease in electrical field intensity with increasing distance from antenna.

Finally, we hope this study contributes to the development of safe and evidence-based exposure guidelines for radiofrequency (RF) radiation, particularly in densely populated areas.

By understanding how crowds influence wave behaviour, we can design future communication systems that minimize human absorption and build public trust in the safety and benifits of wireless technology.

REFERENCES

[1] ICNIRP, (2024). International Non-Ionizing Radiation Protection (ICNIRP) committee. "Guidelines of exposure limits for non-ionizing radiation: http://www.icnirp.org/en/publications/index.html

[2] Ş.S.Şeker. (1995). Multicomponent Discrete Propagation Model of Forest, IEE Proc-Microw. Antennas Propag., Vol. 142. No. 3.

[3] C.Gabriel, and S.Gabriel. (1996). Compilation of The Dielectric Properties of Body Tissues at RF and Microwave Frequencies, King's College, London, UK, 1996, internet article available at: http://niremf.ifac.cnr.it/docs/DIELECTRIC/Report.html

[4] Ş.S.Şeker, (2017). Electromagnetic Radiation Exposure of Crowd at GSM Frequencies. *International Journal of Modern Research in Engineering and Technology (IJMRET) www.ijmret.org Volume 2 Issue 8 ǁ December 2017.*

[5] Adewusi, S. (2014). Modal parameters of the human hand-arm using finite element and operational modal analysis. Article in Mechanics and Industry November 2014. DOI:10.1051/meca/2014060. Article published by EDP Sciences. https://www.researchgate.net/publication/277684441

[6] YOLDAŞ1, A, DEMİR2, M, CALISGAN3, E, (2019). The Comparison of Measurements of the Wrist, Palm, and Finger Parameters Between Female and Male. *KSU Medical Journal 2020;15(1): 6-10.*

[7] P.P. Pathak, H. Tripathi, V. Kumar (2010). Specific Absorption Rate Calculation and Rate of Temperature Change in Tissues Due to Radio Antenna. *International Transactions in Applied Sciences July-September 2010, Volume 2, No. 4, pp.739-747.* : https://www.researchgate.net/publication/234093141

[8] AMRANI1, L, MAZRI2, T,.HMINA, N (2020). Specific Absorption Rate Calculation Model in Case of Exposure to Microwaves Sources. *Romanian Journal of Information Science and Technology. Volume 23, Number 3, 2020, 274–291*

[9] Alaa, M, Hediya, A, (2022). Reduction of Specific Absorption Rate. *The Egyptian International Journal of Engineering Sciences and Technology, Vol. 39 (2022) 80–96.* https://eijest.journals.ekb.eg/

[10] Prof. Dr. G. Keith, (2019). Crowd safety and Crowd Risk Analysis. https://www.gkstill.com/Support/crowd-density/CrowdDensity-1.html