A Computational Presentation of Bioelectromagnetic Applications using Numerical Method Approaches

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***Abstract* — This paper presents a visualization of electromagnetic wave in term of wave movement and behavior. The application of computational electromagnetic waves is from biological system application such as membrane human skin cell and the propagation of waves were analyze with electric field, skin depth and attenuation coefficients at low frequency. Finite Difference Time Domain Method (FDTD) as a engine behind mathematical model and Maxwell equation derivation. The verification of graphical modeling was made with previous researchers.**

***Index Terms*——Electromagnetic, Radiation, Finite Difference Time Domain, Electric Field, Matlab.**

I. Introduction

Nowadays, more electrical and electronic equipment produced and each device will emit electromagnetic waves intentionally or unintentionally. It threatens the world during the 24 hours when using a mobile phone, computer, electrical items and equipment that emits waves. Long exposures to low-power electromagnetic waves have the potential to effect human health. The impact will not appear immediately because these may affect human cells in the future if exposed for too long. When radiation enters human cell, the component of the cell will react through kinetic energy.

There are three phenomena can be considered as the effects of the interaction of electromagnetic radiation with biological tissues such as the EM wave’s penetration into the living system and their propagation into it. Besides that, the possible secondary effects induced by the primary interaction and the primary interaction of the waves with biological tissues [1].

The motion of electrically charged particles produced electromagnetic waves. These waves are also called "electromagnetic radiation" because they radiate from the electrically charged particles. They travel through empty space as well as through air and other substances. Electromagnetic radiation is a particular form of the more general electromagnetic field (EM field), which is produced by moving charges. Electromagnetic radiation is associated with EM fields that are far enough away from the moving charges that produced them, that absorption of the EM radiation no longer affects the behaviour of these moving charges.

There are many mathematical models which available today still can't be proved in order to relate them with electromagnetic wave on human being. Matlab and GUI is used to assist the understanding on how electromagnetic wave effecting human cell. The Maxwell equation will be used as the basic of the modelling in this project with the aid of numerical method approaches especially Finite Difference Time Domain technique.

General Medical Sciences (NIGMS) USA was done their research about Human skin cell sizes at 2008. The size was reported as shown in table 1. This size is very important in this project because this size will be used as cell size when modeling the structure of cell in MATLAB software.

Table 1
Human skin size

Cell portion	Actual size average
Cell diameter	40 micrometer
Nucleus diameter	3 micrometer
Membrane diameter	4 micrometer
Substances in cell	20-30 micrometer

II. Theory and Numerical Solution

The FDTD technique, as introduced by Yee in 1966, has been proven to be a convenient and effective tool for time-domain analysis of various electromagnetic scattering

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problems involving arbitrarily shaped objects. The advantage is its extensive applicability to inhomogeneous, anisotropic, dispersion and non-linear problems. By combining the time step with the space step in calculation, the results in whole frequency band can be obtained by one-run of the calculation, which makes this method especially suitable for wide frequency band analysis.

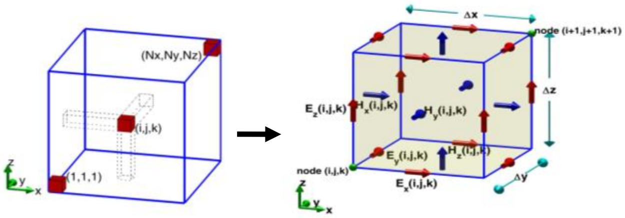

Figure 1: Yee Cell

The basic formulation that governs the interaction of electromagnetic waves and human cell is a Maxwell's equations that consist of the following [2]:

$$\nabla \times \bar{E} = \frac{-d\,\bar{B}}{dt}$$
$$\nabla \times \bar{H} = \bar{J} + \frac{d\bar{D}}{dt}$$
$$\nabla . \bar{B} = 0$$
$$\nabla . \bar{D} = \rho_v \qquad (1)$$

Assume that the single human cell is made of isotropic, homogeneous and free of source medium. In a region with no charges ($\rho = 0$) and no currents ($J = 0$), such as in a vacuum, Maxwell's equations reduce to:

$$\nabla \times \bar{E} = \frac{-d\,\bar{B}}{dt}$$
$$\nabla \times \bar{H} = \frac{d\bar{D}}{dt}$$
$$\nabla . \bar{B} = 0$$
$$\nabla . \bar{D} = 0 \qquad (2)$$

Helmholtz wave equation will be produced after we manipulate equation (2). It adequately describes the propagation of electromagnetic wave. The wave equation for the electric field can be presented as below:

$$\nabla^2 \bar{E} = \mu\varepsilon \frac{d^2 E}{dt^2} \qquad (3)$$

Considering a y-polarized TE mode which propagates in the z-direction and β as a propagation constant in longitudinal direction will then yield:

$$\frac{d^2 E_y}{dx^2} + \frac{d^2 E_y}{dy^2} - \beta^2 E_y = -\bar{\omega}\mu\varepsilon E_y \qquad (4)$$

Taking $k^2\omega$ as the total propagation of electromagnetic wave constant which combines the horizontal and vertical part will then produce:

$$\frac{d^2 E_y}{dx^2} + \frac{d^2 E_y}{dy^2} + (k^2 - \beta^2) E_y = 0 \qquad (5)$$

Knowing that k is a multiplication of free space propagation constant, k_o and permeability, μ or permittivity, ε respective for n in single human cell, equation (5) can be written in the form of:

$$\frac{d^2 E_y}{dx^2} + \frac{d^2 E_y}{dy^2} + ({k_o}^2 n^2 - \beta^2) E_y = 0 \qquad (6)$$

In the application of finite difference method to solve equation (6) above, the E field and the permeability value, n, is considered to be a discrete value at respective x- and y coordinate and bounded in a box, which represent the wave cross section. The box is divided into smaller rectangular area with a dimension of Δx and Δy in x- and y directions respectively.

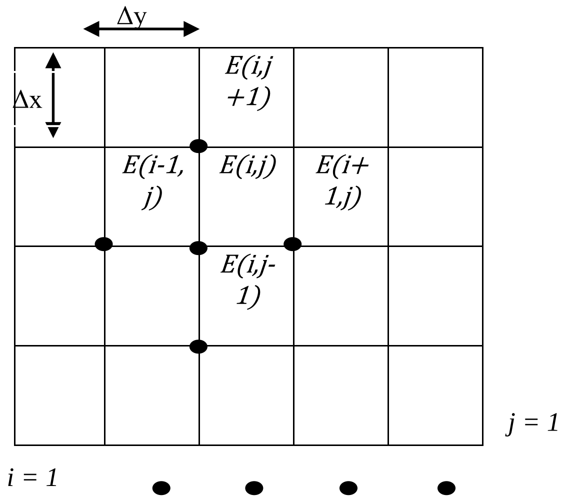

Figure 2: Cross section area

Figure 2 show the waveguide cross section area is dividing into M x N grid lines, which corresponds to the mesh size of Δx and Δy. It shows the presentation of the axis, meshes and grid lines for the finite difference calculation.

Considering the Ey having component in is applied to equation FDTD application at the meshing techniques x and y direction E(x,y), Taylor's expansion is applied where the differential components are obtained as follows:

$$\frac{d^2 E}{dx^2} = \frac{E(i+1,j) + E(i-1,j) - 2E(i,j)}{\Delta x^2}$$
$$\frac{d^2 E}{dy^2} = \frac{E(i+1,j) + E(i-1,j) - 2E(i,j)}{\Delta y^2} \qquad (7)$$

Combine equation (6) and (7) will give a basic equation to obtain the electric field:

$$E(i,j) = \frac{E(i,j) + (i-1,j) + \frac{\Delta x^2}{\Delta y^2}\left(E(i,j+1) + E(i,j-1)\right)}{2\left(1+\left(\left(\frac{\Delta x^2}{\Delta y^2}\right)^2\right)\right) - \Delta x^2\left(k_0^2 n^2(i,j) - \beta^2\right)} \quad (8)$$

Equation (5) is multiplied with E_y and operating double integration towards x and y, it will produce:

$$\beta^2 = \frac{\iint E_y\left(\left(\frac{d^2E_y}{dx^2} + \frac{d^2E_y}{dy^2}\right) + k_0^2 n^2 E_y\right)dxdy}{\iint E_y^2\,dxdy} \quad (9)$$

Further application of finite difference time domain method and trapezoidal rule to equation (9) shall then produce:

$$\beta^2 = \frac{\sum_{i=1}^{N-1}\sum_{j=1}^{N-1} E(i,j)\left[\frac{E(i-1,j) + E(i-1,j) - 2E(i,j)}{\Delta x^2} + \frac{E(i,j+1) + E(i,j-i) + 2E(i,j)}{\Delta y^2} + k_o n^2(i,j)E(i,j)\right]\Delta x\Delta y}{\sum_{i=1}^{N-1}\sum_{j=1}^{N-1} E^2(i,j)\Delta x\Delta y} \quad (10)$$

Equation (10) above is obtained by applying Dirichlet boundary condition which states the E (i, j) = 0 at the boundary. Initial value of E (i, j) = 1 is set for other points. In order to speed up the process, a successive over relaxation (SOR) parameter, C introduced to Equation (8), which states that the iteration will converge faster for C between 1 and 2. Taking SOR parameter into consideration will modify Equation (8) to be:

$$E(i,j) = C\left(\frac{E(i,j) + (i-1,j) + \frac{\Delta x^2}{\Delta y^2}\left(E(i,j+1) + E(i,j-1)\right)}{2\left(1+\left(\left(\frac{\Delta x^2}{\Delta y^2}\right)^2\right)\right) - \Delta x^2\left(k_0^2 n^2(i,j) - \beta^2\right)}\right) - (C-1)E(i,j) \quad (11)$$

The decide tolerance will produce the final value of β and the TE field distribution for the entire membrane of the fundamental mode is related to the propagation constant by $\frac{\beta\lambda}{2\pi}$. When the electromagnetic wave enter into the membrane of cell consider the equation of wave is

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} = (\mu_0 \varepsilon_0)\varepsilon_r\left[\frac{\delta^2 E}{\delta t^2}\right] \quad (12)$$

Where μ_o is the magnetic permeability of vacuum so assume μ_o:1. For most material the induced magnetic polarization is parallel to H in this case the materials are called isotropic. Thus, suscepbility, X is a scalar quantity and vectors M and B have the same direction. This mathematical calculation will be developing into computer programming using MATLAB and the result can be show later.

Three assumptions were considered in this project. First, cell as box and have flat surface. Second, wave propagates only in one point and one side of the cell. Third, cell is damage when field penetrate the wave into the cell nucleus.

Table 1 below show parameter considered in Matlab software which is the value of permittivity and conductivity taken from compilation of the dielectric properties of body tissues at Radio Frequency and Microwave Frequency [3].

TABLE 1
THE VALUE OF PERMITTIVITY AND CONDUCTIVITY TAKEN FROM THE ENGINEERING SOURCES.

Freq (GHz)	Layer 1 (lipid)		Layer 2 (protein)		Layer 3 (fat)	
	σ_{eff} (S/M)	ε_r	σ_{eff} (S/M)	ε_r	σ_{eff} (S/M)	ε_r
2.4	0.61	53	0.50	44.61	0.039	17.02
4.5	0.72	51.31	0.55	42.48	0.045	15.03
9	0.867	41.4	0.59	38.9	0.109	11.3

Matlab software consists of three main components which are inputs parameters, data processing and final output. As for input parameter, the input is required by algorithm of the Finite Difference time Domain (FDTD) method. Inputs are used to control the sequence of the application. The data obtain will be used for calculating the output or to be transformed to other form of data.

III. RESULTS AND DISCUSSIONS

The cell was designed using 2D dimension as shown in Figure 3. The human skin cell was designed according to the standard cell size from General Medical Sciences (NIGMS) USA cell size measurement. We assume that the cell is in rectangle shape.

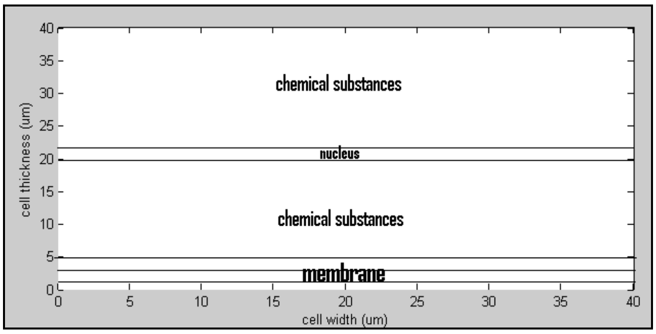

Figure 3: Cell design in 2D dimension.

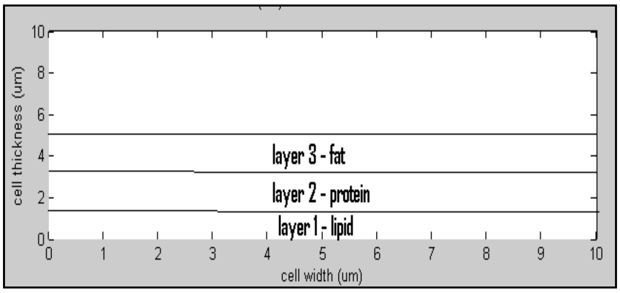

Figure 4: Three Layer of Membrane.

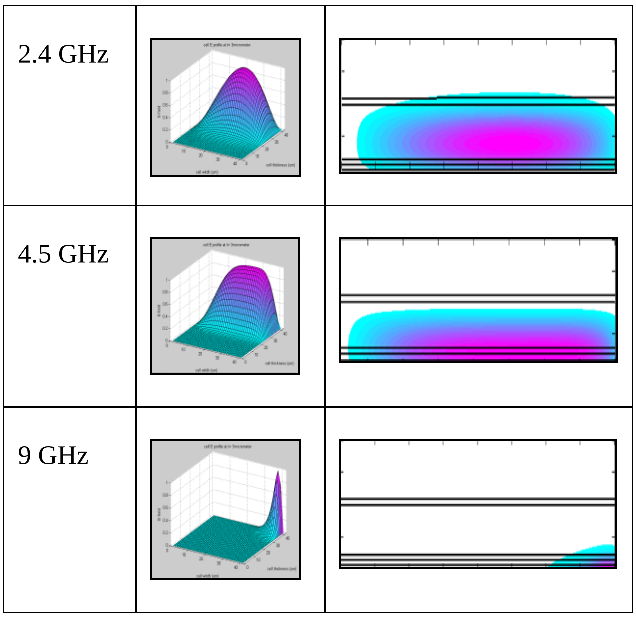

Figure 5: Movement of E-field at three different frequencies

Figure 5 show the E-field contour at 2.4 GHz was refracted to chemicals and nucleus. At 4.5 GHz, it show the E-field propagate only in chemical substances in human skin cell. While for the E-field at 9 GHz propagate near the third layer of cell membranes.

When the electromagnetic wave propagates from a source transmitter to human skin cells, electromagnetic waves will be first interact with cell membranes. Eo value is obtained when the electric field is the highest in the first layer. When the wave propagates into second layer and so on, the electric field will decrease due to absorption of energy in human cells. Eo vs layer graph shows exponential decline.

Increasing in frequency will reduced Eo and further penetrate of electromagnetic waves into human cells will reduce the electric field. When electromagnetic wave penetrates into second layer and third layer, more energy ware absorbed by cell and it cause Eo reduced.

TABLE 2

COMPARISON E-FIELD VALUE FOR DIFFERENT FREQUENCIES

Frequency	**Layer 1**	**Layer 2**	**Layer 3**
2.4 GHz	0.8213	0.6487	0.339
4.5 GHz	0.7608	0.5187	0.3024
9 GHz	0.7268	0.3892	0.2609

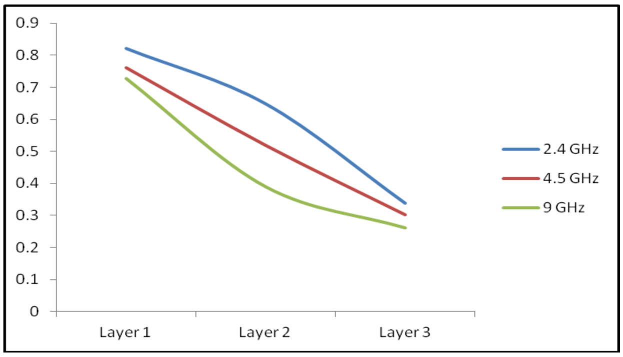

Figure 6: Graph of Comparison E-field value for different frequencies

Attenuation is a function of the permittivity and conductivity of the material, and of the frequency. The attenuation constant α is calculated as below:

$$\alpha = \omega\sqrt{\left(\frac{\mu'\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\sigma eff}{\omega\varepsilon'}\right)^2}-1\right)\right)}\,.(Np/m)$$

The attenuation is used to determine an important parameter called skin depth. Skin depth is the distance the wave propagates before its magnitude has dropped to 1/e=0.37, or about 1/3 of its original value. Skin depth is given by 1/α, and its unit is in meter.

TABLE 3

ATTENUATION VALUE

Freq	Layer	Attenuation (α)	E_0
2.4 GHz	Lipid	15.772	$e^{-15.772z}$
	Protein	14.172	$e^{-14.172z}$
	Fat	0.178	$e^{-0.178z}$
4.5 GHz	Lipid	18.932	$e^{-18.932z}$
	Protein	15.878	$e^{-15.878z}$
	Fat	2.188	$e^{-2.188z}$
9 GHz	Lipid	25.361	$e^{-25.361z}$
	Protein	17.858	$e^{-17.858z}$
	Fat	6.109	$e^{-6.109z}$

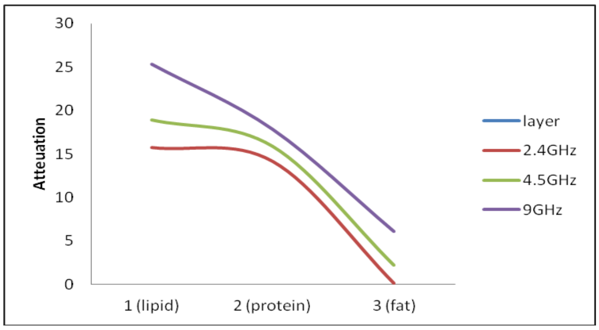

Figure 7: Graph of Attenuation vs 3 layer at different frequencies.

Skin depth is the distance at which the wave has decreased to $1/eE_o$ of its original value due to attenuation loss in the tissue. Tissues with higher water content as example lipid are more conductive and therefore have smaller skin depths which fields do not penetrate far into this cell. Lowering the frequency always increases the skin depth or how far the wave will propagate in the cell.

Skin depth is given by 1/α, and its unit is in meter. Skin depth is the distance the wave propagates before its magnitude has dropped to 1/e=0.37, or about 1/3 of its original value. Table 3 below shows all the skin depth value at different layer and different frequency.

TABLE 3:
SKIN DEPTH VALUE

F(Hz)	Layer	1/α (m)	Total
2.4G	Lipid	0.06340	5.75550567
	Protein	0.07056	
	Fat	5.62154	
4.5G	Lipid	0.05282	0.57284544
	Protein	0.06298	
	Fat	0.45705	
9G	Lipid	0.03943	0.25912039
	Protein	0.05600	
	Fat	0.16369	

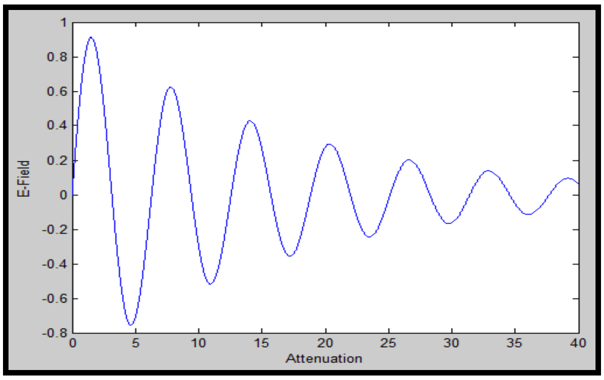

Figure 8: The value of skin depth at 2.4 GHz.

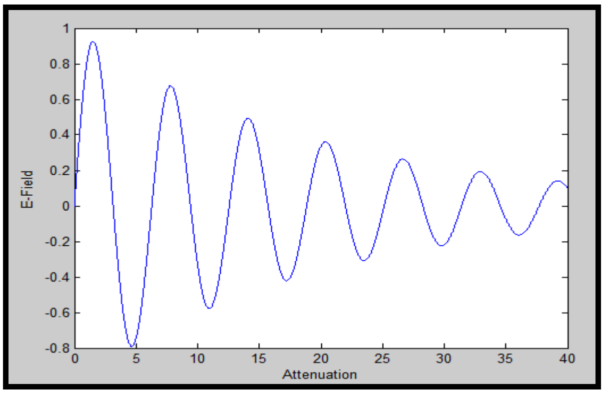

Figure 9: The value of skin depth at 4.5 GHz.

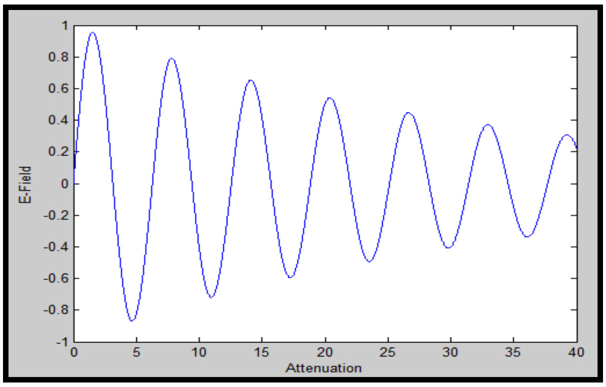

Figure 10: The value of skin depth at 9 GHz.

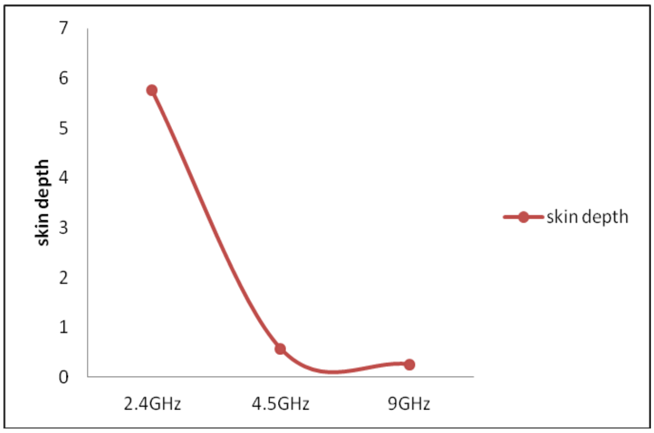

Figure 11: Graph of skin depth vs frequency

From that the attenuation is indirectly proportional with skin depth. Note that frequency increases the attenuation so that skin depth was decrease. As the frequency increased, the penetration generally becomes less.

By using Matlab modeling from three different frequencies, we can see that the low frequency can propagate far deep into human cell but high frequency of electromagnetic waves cannot propagate far into human cell and cannot penetrate the cell other than cell membrane. In this case, the cell has high probability of being damaged.

The interaction between electromagnetic waves and first layer of membrane cell produced the high E_o. The value of E_o was decreased when electromagnetic waves propagate to second layer and go on to other inner human cell. The value of E_o will decrease when the frequency is increase. In beginning, assumptions is made which is when electric field penetrated into chemicals and nucleus, the cell was damage. This proven with 2.4 GHz which the pattern of contour penetrates until nucleus compared with 4.5 GHz and 9 GHz frequency.

After obtaining the electric field value, the attenuation was calculated. The relation between electric field value and attenuation is mentioned in this formula, Eo= e-αz. The attenuation at 2.4GHz more lowers than others frequency because it is less losses. If the value of attenuation is low, the wave will penetrated far and it is known as skin depth or penetration depth. The distance of e-field penetrated in the cell depends on the distance of penetration depth.

Generally, the penetration of incident field into biological bodies decreases as frequency increases. In this project, membrane cell is 4 micrometer so the wave was propagates within this distance before e-field refracted to others cell partition. From theory, the attenuation indirectly proportional with skin depth, so result of this project is agreeable with theory.

The value of permittivity and conductivity is the main factor to obtain the value of attenuation and skin depth. From this project, it proves that when human skin cell interact with electromagnetic waves at lower frequency is more dangerous than higher frequency.

IV. CONCLUSION

In this paper, a numerical technique which is Finite Differences Time Domain (FDTD) has been used to investigate the interaction of electromagnetic fields with human cells. Using Matlab and calculation, we can see that the low frequency can propagate far deep into human cell but high frequency of electromagnetic waves cannot propagate far into human cell and cannot penetrate the cell other than cell membrane. This shows electromagnetic waves can propagate over long distances in a lower frequency.

Assume that the electromagnetic waves propagating to the nucleus and the electric field is still high in the third layer of membrane, human skin cells are damaged. Once the cells are damaged can be result to many diseases such as skin cancer and it is very dangerous to humans.

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