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EFFICIENCY DYNAMICS OF WIRELESS MOUSE ANTENNA INFLUENCED BY POSITION OF USER'S INDEX FINGER

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Abstract- In this paper, Finite Difference Time Domain (FDTD) and the Method of Moments (MoM) are used to analyze the effect of a human hand index finger on a wireless mouse antenna. The important parameters of the wireless mouse that are affected by a human hand index finger such as input resistance, reflection coefficient, bandwidth (resonance frequency) and efficiency, have been evaluated. It is established that the index finger decreases the input resistance of the mouse. The results show that the finger also reduces the efficiency of the mouse antenna. This can be explained by the fact that the human hand absorbs energy. It was further established that the wireless mouse antenna's efficiency depends on the position of the index finger. When the finger is at the middle of the mouse antenna, the efficiency is relatively low. Moving the finger along the wireless mouse antenna, to either the right or to the left of the feed point, increases the efficiency rapidly. Beyond a certain distance on either side, there is rapid deterioration of the wireless mouse antenna's efficiency.

Keywords: Antenna Dipole, Efficiency, Electromagnetic Field, FDTD, Wireless Mouse.

I. INTRODUCTION

One of the accessories that come with a computer is the mouse. It has become an extremely popular technology because it is more convenient for a user to point at an object on the display instead of typing a command [1]. Among any hardware part in a wireless mouse, the antenna is a key element. Design engineers are therefore placing greater emphasis on antenna designs that improve its in-use performance [2].

Mouse technology has changed in very significant ways in the last fifteen years. Focus now is, not only on functionalities, but also on design and aesthetics of the devices. At the same time, users' appetite for better performance and more services has increased. Users are now expecting more attractive and better performing devices [3]. Therefore, wireless mice designers have the challenge of meeting these demands. However, it is hoped that this design challenge can be helped by the many computer-assisted numerical techniques that can simulate different situations. The FDTD method, based on the Yee's algorithm introduced in 1966 [4] has proved more accurate and hence reliable over the years for simulating new antenna designs for optimum performance.

Former antenna design studies, including human interactions [5, 6] have particularly focused on mobile phones handsets especially the effect of the head on the antenna. However, recent studies [7, 8], stated that the hand effects were way larger than the head ones. Among the parts of the hand, the index finger plays a very significant role.

This study sets out to analyze the effects of the index finger, particularly on wireless mouse antenna, in order to facilitate its design process in the future. In order to limit the study scope, only one way of holding the mouse will be considered. Furthermore, the difference between male and female hands is beyond the scope of this study.

This paper is divided into four sections. The first part provides ample background on the topic. The second section focuses on the material and method of calculation (FDTD). It discusses the modelling of a dipole in free space and modelling of the index finger. The results of the interaction between the wireless mouse and the index finger are given in section III. The section also gives the illustration of the effect of the finger position on the wireless mouse radiation efficiency. Finally, we present our discussion in section IV.

II. MATERIAL AND METHOD

The choice of numerical technique generally depends on the geometry of the problem and the accuracy of desired solution [9]. FDTD is one of the three primary numerical analysis methods in electromagnetic. MoM and finite element method (FEM) are also commonly used. Both FEM and FDTD method solve for unknown electric and magnetic fields in the simulation area while MoM solves for unknown surface and volume currents on perfect electric conductors (PECs). Using the method of moments can significantly reduce the number of unknowns when only PEC and perfect dielectrics are present, but this is not the case with the human hand, which is quite loss. FEM analysis is conducted on a mesh which can be somewhat arbitrarily defined as long as it follows certain guidelines.

This makes FEM a more flexible solution when solving complex geometries. However, FEM also requires solving a matrix equation that takes a great deal of computation. The FDTD method must use a grid of fixed size, but it is an iterative method that computes field values over a large number of time steps and solves a given number of unknowns faster than FEM [10].

Since this research required a large number of simulations, the speed of the solution is important. Thus, because of this and because FDTD requires less memory than FEM, the FDTD method was chosen. However, in this study, MoM was used only for validation of the results.

A. FDTD Formulation

In FDTD, both space and time are divided into discrete segments. The division of space is referred to as spatial discretization and the division of time is called temporal discretization. Spatial discretization is done by dividing the computational space into cubical cells called Yee cells [4] as shown in Figure 1.

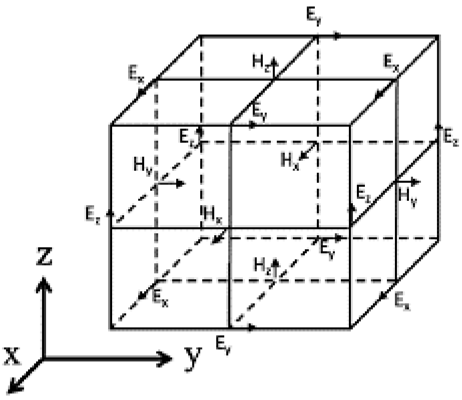

Figure 1. Positions of the electric and magnetic field components in a Yee cell [4]

From Figure 1, it can be seen that electric field components of $E_x(i,j,k)$, $E_y(i,j,k)$ and $E_z(i,j,k)$ are located at Yee-cell edge centres and magnetic field components of $H_x(i,j,k)$, $H_y(i,j,k)$ and $H_z(i,j,k)$ are located at face centers. The magnetic and electric fields are offset both in space and time. The computation space is assumed to be filled with a number of Yee-cells resulting in a three-dimensional volume called an FDTD grid or mesh. Each Yee-cell is identified by the spatial discretization indices (i,j,k). These indices are mapped to the physical space as per the following relation.

$$(i,j,k) \rightarrow (i\Delta x, j\Delta y, k\Delta z)$$

The temporal discretization index n corresponds to the real time, $n\Delta t$.

B. Numerical Dispersion

The dimensions of the cells are carefully determined in order to be sufficient to resolve the shortest wavelength of the electromagnetic waves used in the simulations. If this is not done, an error due to the difference between the values of numerical phase velocity and analytical phase velocity will be quite large. Care should therefore be taken so as to reduce this error as much as possible. The reduction of this error results in more accurate simulations. The following section describes how this is done [11].

First, the shortest wavelength is calculated using the formula:

$$\lambda_{\min} = \frac{c}{f_{\max} n_{\max}} \tag{1}$$

where $f_{\max}$ is the highest frequency in the propagating wave or signal which corresponds to the shortest wavelength and $n_{\max}$ is largest refractive index found anywhere in the computational space. The $n_{\max}$ is calculated as follows:

$$n_{\max} = \sqrt{\mu_r \varepsilon_r} \tag{2}$$

where μ_r and ε_r are relative permeability and permittivity of the material used in the simulations.

Second, the wave is resolved with at least 10 cells:

$$\Delta_\lambda = \frac{\lambda_{\min}}{N_\lambda} \tag{3}$$

where $N_\lambda \geq 10$ and Δ_λ is the dimension of the cube.

C. Numerical Stability

Temporal discretization is done by partitioning the total simulation time into small time steps denoted Δt. Each time step is the period a field takes to travel from one cell to the next.

Due to numerical dispersion, a numerical wave can suffer from non-physical attenuation or be amplified so that the simulations become unstable depending on the value of the imaginary part of angular frequency. This instability is a source of error during simulations. To guarantee stable simulations, the time step used should be determined carefully. The following section describes how this is done.

Electromagnetic waves propagate at the speed of light in a vacuum. Inside a material, they propagate at a reduced speed v given by

$$v = \frac{c}{n} \tag{4}$$

where c = 299792458 m/s which is the exact speed of light in a vacuum, and n is the refractive index of the medium.

Over duration of one time step Δt, an electromagnetic wave will travel a numerical distance equal to Δ_λ .The physical distance covered in one time step is $c.\Delta t/n$. Because of the numerical algorithm, it is not possible for a wave to travel farther than one unit cell in a single time step. It is therefore important to make sure that a physical wave will not travel farther than a unit cell in one time step i.e.,

$$\frac{c\Delta t}{n} < \Delta_\lambda \tag{5}$$

This places an upper limit on the time step i.e.

$$\Delta t < \frac{n\Delta_\lambda}{c} \tag{6}$$

The value of n should be set to the smallest refractive index found anywhere in the grid. Usually, this is just made to be 1 and dropped from the equation. Thus with n set equal to 1, the fastest possible physical wave has a time step given as

$$\Delta t < \frac{\Delta_\lambda}{c} \tag{7}$$

For two dimensions (2D) or three dimensions (3D) grids, the condition can be generalized as

$$\Delta t \le \frac{1}{c\sqrt{\frac{1}{{\Delta_x}^2}+\frac{1}{{\Delta_y}^2}+\frac{1}{{\Delta_z}^2}}} \tag{8}$$

where Δx, Δy and Δz are the dimensions of the Yee-cell along the x, y and z axis respectively. The above equation represents the Courant stability condition [11].

D. Discretization of Maxwell's Equation Using the Yee Algorithm

During simulations, a method called leapfrog technique is used to update the electric and magnetic fields [4]. For instance, updates for the electric fields come first. This is then followed by the updates of the magnetic ones.

Now we present the Maxwell's equations in three dimensions. We suppose the absence of magnetic or electric current sources and the existence of absorbing materials in the space under study.

$$\nabla \times E + \mu \frac{\partial H}{\partial t} = 0 \tag{9}$$

$$\nabla \times H + \varepsilon \frac{\partial D}{\partial t} = \sigma E \tag{10}$$

where the displacement vector D is related to the electric field through the complex permittivity

$$\varepsilon_r^{\,*}(\omega) = \varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o} \quad \text{by} \quad D(\omega) = \varepsilon_r^{\,*}.E(\omega) \tag{11}$$

where ω is the angular frequency, this gives discretized expressions of the form:

$$\frac{E_x^{\,n+\frac{1}{2}}(k) - E_x^{\,n-\frac{1}{2}}(k)}{\Delta t} = \frac{-1}{\varepsilon_o\varepsilon_r}\,\frac{H_y^{\,n}(k+\frac{1}{2}) - H_y^{\,n}(k-\frac{1}{2})}{\Delta_z} - \\ -\frac{\sigma}{\varepsilon_o\varepsilon_r}\,\frac{E_x^{\,n+\frac{1}{2}}(k) + E_x^{\,n-\frac{1}{2}}}{2} \tag{12}$$

$$\frac{H_y^{n+1}(k+\frac{1}{2}) - H_y^{n}(k+\frac{1}{2})}{\Delta t} = -\frac{1}{\mu_o}\,\frac{E_x^{\,n+\frac{1}{2}}(k+1) + E_x^{\,n+\frac{1}{2}}(k)}{\Delta_z} \tag{13}$$

The Equations (12) and (13) are typical expressions that are used to calculate the values of the electric and magnetic fields during simulations.

E. Computational Models

E.1. Modeling the Wireless Mouse

The wireless mouse was designed as a half wave dipole antenna. A simple dipole antenna that consists of two metallic wire arms is illustrated in Figure 2.

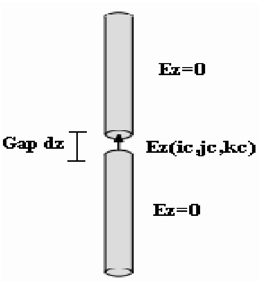

Figure 2. Geometry of the dipole antenna model [12]

Current flowing through the arms results in radiation. FDTD models a dipole this way: The electric field components along the axis of the wire arms are set to zero except in the place where there is a gap. This gap is used by the antenna source. The dipole is fed at the center ($x=x_c.\Delta x$, $y=y_c.\Delta y$, $z=z_c.\Delta z$). This is a gap of length Δz where a sinusoidal wave called source [13] is applied. The magnetic field components are calculated using the normal FDTD equations. The antenna length was held constant at each simulation.

E.2. Electric Current

The current in the antenna at the feed point is obtained by applying Ampere's law [13] to the surface S with the bounding contour C on the wire at (i_c, j_c, k_c+3/2)

$$\oint_c H.dl = \iint J.ds + e_o \iint \partial E / \partial t.ds \tag{15}$$

E.3. Modeling the Human Hand Index Finger

The human hand index finger model was designed as a homogeneous finger using the average dielectric properties of the skin, muscle and bones. These values were determined by *C*. Gabriel and are available in the literature [14]. A simplified homogeneous rectangular finger model was used. These tissue equivalent dielectric parameters were chosen according to [14] to simulate the hand tissue at 2.4125 GHz. Thus, the finger model shape was designed as a dielectric slab. The dimensions of the cubical slab were 1.48×1.48×1.48 cm and the tissue it contained had relative permittivity of ε_r=35.4 and conductivity of σ=1.81 S/m.

III. SIMULATION RESULTS

A. Index Finger Effect on Near Fields, Bandwidth and Radiation Efficiency of Dipole Antenna

A.1. Comparing Input Resistance Using FDTD and MoM

Before embarking on simulations, we developed a 3D FDTD program implemented in Matlab code. We used the code to analyse the variation of input resistance with frequency of a half wave dipole antenna radiating in free space at a frequency of 2.4 GHz. We compared our results with the results for the same analysis which was done using the method of moments in order to validate the Matlab code. As Figure 3 shows, we obtained a very good agreement. In fact, at our frequency of interest i.e. 2.4125 GHz, the difference between the two methods was negligible.

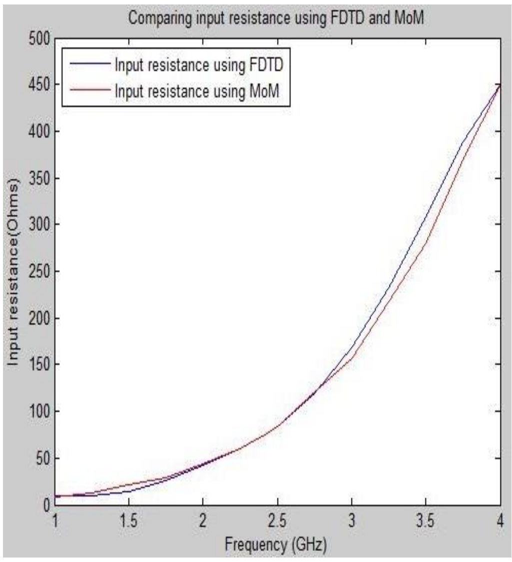

Figure 3. Plot of variation of input resistance with frequency

A.2. Index Finger Effect on Near Fields

Using the 3D FDTD program implemented in the Matlab software, a simulation was carried out to show interaction between a plane wave and free space. The results showed that free space does not absorb power from an electromagnetic plane wave. Furthermore, free space does not distort the wave. However, when a dielectric slab representing the index finger was used, the results confirmed tissues absorb power from an electromagnetic plane wave. Furthermore, the finger distorts the wave.

The index finger can alter the electromagnetic field distribution and absorb power when it enters the reactive near-field of the antenna. In this region, the electric field is strong and since power loss is comparable to the square of the electric field, absorption is large. As the finger moves away from the near field region, the absorbed power decreases.

A.3. Index Finger Effect on Bandwidth

The bandwidth of the antenna, which was determined by the impedance data, is the frequency range of the antenna (less than or equal to 1/3) that corresponds to s11 of -6 dB. It can be seen in Figure 4 that when the antenna was operating in free space, its bandwidth was about 1 GHz (1.9 GHz to 2.9 GHz). However, when the index finger was in close proximity, the bandwidth changed to about 0.5 GHZ (2 GHZ to 2.5 GHz at 0.185 cm). This was a reduction of about 500 MHz. The amount of detuning depends on the antenna shape, the near-fields, as well as on the antenna-finger-separation distance.

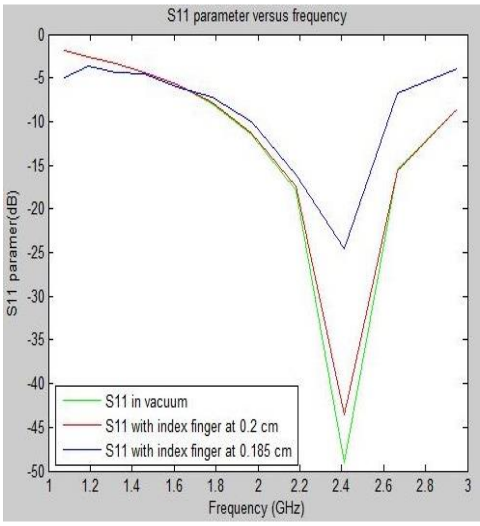

Figure 4. S11 parameter versus frequency

A.4. Index Finger Effect on Radiation Efficiency

Radiation efficiency is defined as the ratio between the radiated to the accepted power by the antenna. Figure 5 shows the efficiency of the dipole antenna when radiating into free space and when radiating in the presence of a hand index finger. As can be seen, the efficiency of the antenna is decreased by the hand index finger. It can be observed that the highest efficiency is obtained at resonance frequency of 2.4125 GHz. At this frequency, we have the lowest mismatch and reflection loses. At any other frequency, these loses are larger. An increase in frequency beyond resonance value, results in more power absorption by the index finger. Thus, there is a rapid decrease in efficiency.

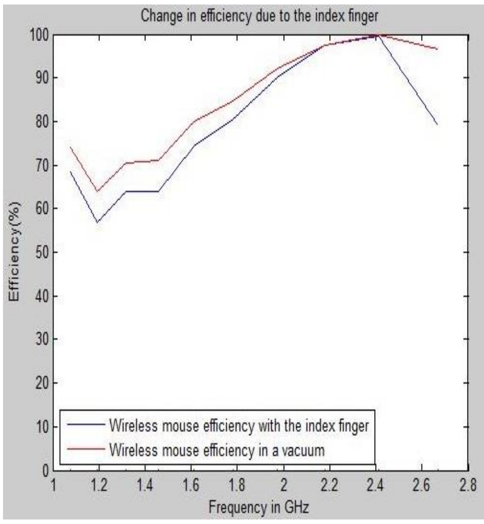

Figure 5. Change in efficiency due to the index finger

B. The Effect of the Index Finger Position from the Antenna Feed Point on Wireless Mouse Radiation

Figure 6 was used as a reference in terms of specifying the position of the index finger. When the finger is said to be at the middle of the wireless mouse the finger is just above the scroll wheel at the middle. In the above figure, the finger is to the left of the middle.

Figure 6. Hand Holding Wireless Computer Mouse (CB107267 Corbis Royalty Free Photograph)

B.1. Index Finger Position Effect on Input Resistance

Figure 7 shows that when the pointing finger is at the middle of the wireless mouse the amount of input resistance is small. As the finger is moved about 0.3 cm to the left the resistance increases. The same case applies when the finger is moved to the right. However, it can be seen that there is no balance in the two arms of the antenna.

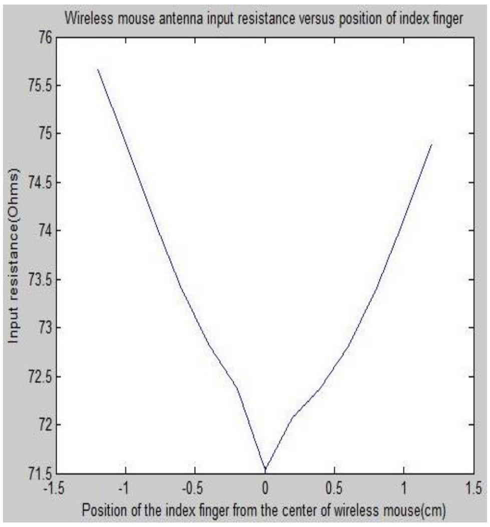

Figure 7. Wireless mouse antenna input resistance versus position of the index finger

B.2. Index Finger Position Effect on Radiation Efficiency

In order to determine the effect on a human hand index finger on the wireless mouse efficiency, it was necessary to ignore the reduction of efficiency due to other dielectrics such as the PCB and mouse plastic cover. In this way, we were able to isolate the effect of the finger tissues. Furthermore, having established that the largest efficiency was obtained at resonance frequency, the frequency was fixed at 2.4125 GHz. This allowed us to concentrate on the impact of the finger position on the antenna radiation efficiency.

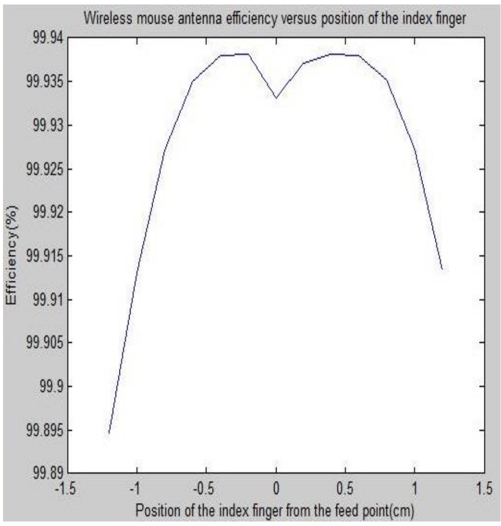

Figure 8. Wireless mouse antenna's efficiency versus the position of the index finger

Figure 8 shows that when the pointing finger is at a distance within the range 0.3 cm to 0.8 cm from the middle of the wireless mouse, we have the largest antenna efficiency. At the middle of the mouse, there is a dip in efficiency because the pointing finger is very near the antenna feed point.

Finger tissues absorb energy. The energy radiated by the wireless mouse antenna is greatest at the feed point. This comes from the radiated power distribution of the antenna, which has a maximum value at the feeding gap. Since the available energy is large at the position, it follows that the index finger will absorb larger amounts of this energy. This explains the dip in the efficiency curve. As the finger moves away from this position, either to the left or right, it absorbs less and less energy. This means an increase in radiation efficiency of the wireless mouse antenna. However, beyond a distance of say, 0.8 cm on either side of the feed point, there is rapid decrease in efficiency. This can be explained by the fact that the radiated energy decreases as the distance from the feed point increases due to dipole antenna characteristics.

IV. CONCLUSIONS

Our Matlab code based on FDTD technique and that was used in the simulations has been validated using MoM and existing data in the public domain. The simulation results show that a human hand index finger influences input resistance, reflection coefficient, bandwidth (resonance frequency) and efficiency of wireless mouse antenna. Our study has established that the index finger decreases the input resistance of the mouse. The effect on bandwidth, for example, depends on the distance of the hand from the mouse antenna: Bandwidth decreases with the decrease in the separation of the hand from the wireless mouse and vice versa. It was established that the hand also reduces the efficiency of the mouse antenna. This can be explained by the fact that the human hand absorbs energy. It was further established that the wireless mouse antenna's efficiency depends on the position of the index finger.

When the finger is at the middle of the mouse antenna, the efficiency is relatively low because the index finger is very near the antenna feed point. At this point, the radiated power is strong and absorption by the nearby index finger is large. This explains the dip in the efficiency curve. Moving the finger along the wireless mouse antenna, to either the right or to the left of the feed point, increases the efficiency rapidly. For instance, when the finger is at a distance within the range 0.3 cm to 0.8 cm from the middle of the wireless mouse, antenna's efficiency is relatively high. However, the antenna's efficiency deteriorates when the finger is located at distances greater than 0.8 cm from the antenna's feed point. This can be explained by the fact that the radiated energy decreases as the distance from the feed point increases due to radiation characteristics of the antenna. At the same time, this decreased energy is further decreased by absorption by the index finger and hence the rapid change.

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