060: A SMART ANTENNA SYSTEM DESIGN FOR LOW-POWER WIRELESS APPLICATIONS

A final year project for the partial fulfillment for the award of a bachelor’s degree in electrical and electronics engineering of the University of Nairobi

PROJECT SUPERVISOR: PROF. V.K. ODUOL

PROJECT EXAMINER: DR. G.S.O. ODHIAMBO

PROJECT UNDERTAKEN BY:

KARIITHI FREDRICK KAMAU        F17/2121/2003
Acknowledgement

I wish to thank my God for the far that He has brought me in my academic pursuits as well as in every other aspect of my life. I also thank my parents and the rest of my family for their moral and financial support throughout this journey. I’m grateful for their love, encouragement, and prayers.

I wish also to thank a friend, Dr. Gatari from the Institute of Nuclear Science, University of Nairobi, for his moral support and every other support he has accorded me to help me get here.

My supervisor, Prof. Oduol has been of great help especially when I’ve seemed to have lost track or felt overwhelmed along the way. I’m sincerely grateful for your input.

Last but not least, my fellow classmates, especially those with whom I’ve consulted the most. God bless you for all the encouraging discourses we have had.

Fredrick K. Kariithi

April/May 2014
### Contents

Acknowledgement ........................................................................................................... ii

List of Figures ................................................................................................................ IV

List of Tables ..................................................................................................................... iv

1. INTRODUCTION ............................................................................................................. 1

   1.0 Smart Antenna System ............................................................................................... 1

       1.0.0 Switched Beam Antennas .................................................................................. 2

       1.0.1 Adaptive Array Antennas .................................................................................. 3

   1.1 The Unlicensed ISM Band ......................................................................................... 4

   1.2 The Elements of a Smart Antenna System ............................................................... 5

   1.3 Direction of Arrival Estimation Algorithms ........................................................... 7

       1.3.0 Least Mean Square (LMS) ................................................................................ 8

       1.3.1 Recursive Least square (RLS) ........................................................................ 8

       1.3.2 Sample Matrix Inversion (SMI) ...................................................................... 9

       1.3.3 Constant Modulus Algorithm (CMA) .............................................................. 10

2. PATCH ANTENNA DESIGN .......................................................................................... 11

3. SIMULATION AND RESULTS ....................................................................................... 13

   3.0 Summary Results of Bending Antenna ................................................................. 20

   3.1 Patch Antenna and Human Body Interactions ....................................................... 21

   3.2 The Specific Absorption Rate (SAR) .................................................................... 22

4. DIGITAL BEAMFORMING SYSTEM ............................................................................ 22

   4.0 Implementation of the Digital Beamforming System ........................................... 22

5. CONCLUSION ................................................................................................................. 23

   5.0 Looking into the Future ............................................................................................ 23

REFERENCES ................................................................................................................... 24
List of Figures

Figure 1.0 Switched beam antenna
Figure 1.1 Adaptive array antenna
Figure 1.2 Comparison between switched beam and adaptive array strategies
Figure 1.3 Switched beam system block diagram
Figure 1.4 Adaptive array system block diagram
Figure 2.0 Patch antenna as it appears in CST Microwave Studio
Figure 2.1 Patch antenna with the port shown
Figure 3.0 The resonant frequency is found to be 2.4454 GHz
Figure 3.1 The -10dB bandwidth is 89.7 MHz
Figure 3.2 3-D farfield characteristics
Figure 3.3 Polar farfield characteristics
Figure 3.4 (a-f) Patch antenna bent around various radii
Figure 3.5.0 Return loss with R=200
Figure 3.5.1 Farfield directivity with R=200
Figure 3.6.0 Return loss with R=100
Figure 3.6.1 Farfield directivity with R=100
Figure 3.7.0 Return loss with R=80
Figure 3.7.1 Farfield directivity with R=80
Figure 3.8.0 Return loss with R=50
Figure 3.8.1 Farfield directivity with R=50
Figure 3.9.0 Return loss with R=30
Figure 3.9.1 Farfield directivity with R=30
Figure 3.10.0 Return loss with R=20
Figure 3.10.1 Farfield directivity with R=20

List of Tables

Table 1 Summary results of bending antenna
Table 2 Electromagnetic properties of the human body tissues at 2.45 GHz
1. INTRODUCTION

1.0 Smart Antenna System

A smart antenna system is an array of antenna elements working in conjunction with signal processors to enable the antenna dynamically steer its beam pattern in the direction of the signal of interest while placing nulls in the direction of the unwanted signals. In essence, a smart antenna has the capability to constantly adjust in accordance with its signal environment.

Smart antennas have been in use for quite a while in defense systems. The cost of implementation has made it difficult to use them commercially. In recent times, however, cost-effective, high-speed technology in areas such as general-purpose processors, analogue to digital converters (ADCs), digital to analogue converters (DACs), digital signal processors coupled with advanced algorithms have made it possible to deploy smart antennas in mobile phone communication [1]. With the explosion of wireless communication networks, smart antenna systems are increasingly finding use due to the benefits they present.

One of the biggest challenges facing wireless communication today is meeting the demand for capacity. This demand continues to grow day by day. This demand is brought about by not only an increase in the number of users, but also in the number of applications that handle voluminous data. It is estimated that by 2016, mobile devices connected to the internet will hit the 10 billion mark versus an estimated human population of 7.3 billion then. Of these, about 8 billion will be personal while the remainder will constitute machine-to-machine connections. From 2011 through 2016, mobile data traffic is expected to grow up to 18 times, the traffic from tablets up to 62 times, while content that is streamed by 28 times. About 90% of this mobile data traffic will be generated by portable devices such as laptops, smartphones, etc. 5% will be generated by machine-to-machine communications and the remaining 5% will come from residential broadband mobile gateways. Mobile video alone constitutes a big percentage of all the mobile data traffic, up to 71%. By the end of 2016, it is anticipated that mobile data traffic will exceed fixed data traffic by 3 times [2].

What limits the performance of wireless communication include co-channel interference which arises from other users trying to communicate at the same frequency, intersymbol interference (ISI), and fading of the signal which is caused by multipath since the signal follows different
paths to the receiving antenna. The fact that interference can arise from different users limits the system's capacity. With an ability to steer its beam, a smart antenna system can increase its sensitivity in the directions of the signals of interest and place nulls in the directions of interfering signals increasing the system's capacity. Attenuation can be done for multipath components which arrive at the receiver from different directions. This has the effect of mitigating signal fading as well as ISI. The benefits that arise out of mitigating the effects of multipath are higher rates of data and an improved bit error rate (BER) performance [3].

Smart antenna systems are broadly categorized as either switched beam or adaptive array antennas. The difference arises from how they steer their radiation patterns.

1.0.0 Switched Beam Antennas

Switched beam antenna systems have a finite number of fixed beams with enhanced sensitivity in specific directions. This antenna system switches the most appropriate fixed beam based on the strength of the detected signal. The system also switches from one fixed beam to another in accordance with the movement of the mobile device throughout the sector.

![Figure 1.0 Switched beam antenna](image-url)
1.0.1 Adaptive Array Antennas

The most advanced smart antenna approach today is implemented through the adaptive array technology. A weight is normally assigned to each antenna array element and is constantly updated to reflect the changing signal environment. This is done in order to increase the antenna gain in the desired direction while attenuating in the direction of the unwanted signal. In essence, the adaptive antenna system effectively monitors its ever changing signal environment in order to dynamically respond to it with a view of enhancing the signal to noise ratio for a signal of interest. This is achieved by employing a motley of innovative signal-processing algorithms. Thus the process can be referred to as adaptive beamforming or digital beamforming [4].

![Figure 1.1 Adaptive array antenna](image)

![Figure 1.2 Comparison between switched beam and adaptive array strategies](image)
In brief, some of the advantages of smart antenna systems are listed below:

- Reduction of co-channel and adjacent channel interference
- Reduction of intersymbol interference
- Better bit error rate performance
- Higher data rates
- Higher receiver sensitivity
- Improved bandwidth utilization
- Power economy
- High security level

The downside to the use of smart antenna technology is that it is more expensive than conventional antenna technology.

Areas in which smart antenna systems find use include the following:

- Mobile phone communication
- Wireless communication
- Cognitive radio
- Radar
- Sonar

1.1 The Unlicensed ISM Band

ISM stands for Industrial, Scientific, and Medical frequency band, viz. 902-928, 2400-2483.5, 5725-5850 MHz. The fact that a spectrum is unlicensed means that everyone is free to make use of it. Of course, this presents a number of advantages over the licensed spectrum. However, while the spectrum can be shared and reused by a motley of applications in order to satisfy the market’s demands for speed and flexibility, the unlicensed spectrum presents the possibility of mutual interference. We cannot rule out the possibility of insufferable interference arising from an overcrowding of users each trying to make use of an otherwise limited resource [5].

Back in 1985, the US Federal Communications Commission okayed the use of the ISM bands by intentional radiators at power levels no greater than a watt without acquiring an end-user license.
Initially, these frequency bands had been set aside for unwanted, but inescapable radiation from mainly industrial processes although a small number of communication users, often military, were also included. These new rules fueled the development of a sizable number of both consumer and professional products. Furthermore, it is regarded as a key step in the technological progress of wireless computing [6]. ISM band has found use in the following applications:

- Wireless local area networks (WLANs)
- Cordless phones
- Remote control
- Wireless telemetry such as monitoring electrical power consumption, medical telemetry, etc
- Domestic microwave oven
- Electronic toll collection
- Providing private point to point links

There are rules regarding the power output levels for ISM bands. They are listed below:

i. The maximum transmitter output power is 1 Watt (30 dBm)
ii. The maximum equivalent isotropic radiated power (EIRP) is 4 Watts (36 dBm). This means that for every dB of antenna gain above 6dBi, the transmitter output power must be decreased by 1 dBm. According to this rule, a 24 dBi antenna limits the output power to 12 dBm or 16 mW
iii. For a fixed point to point in ISM 2.4 GHz, the peak output power is decreased by 1 dBm for every 3 dBi of the antenna gain above 6dBi. According to this rule, a 24 dBi antenna may have an input of 24dBm or 250 nW
iv. In ISM 5.8 GHz, the maximum EIRP allowed is 53 dBm (30 dBm plus 23 dBi of antenna gain)

1.2 The Elements of a Smart Antenna System

The switched beam antenna system as shown in Figure 1.4 below is made up of a phase shifting network. This forms lobes facing particular directions. The radio frequency (RF) switch activates
the appropriate lobe in the desired direction, a selection that is made by the control logic unit. The control logic is in turn directed by an algorithm which checks all the lobes to find out which one receives the strongest signal as measured by the detector. This system is fairly cheap to implement. While being simple, this technique is unsuitable for application in areas which suffer high levels of interference [6].

An ambiguity may arise regarding the detection of the direction of a received signal where a lobe is switched on due to multipath effect instead of the direct signal. Another challenge with this system is call loss before successful hand off as a user moves from an area served by one beam into another.

![Figure 1.3 Switched beam system block diagram](image)

What makes an antenna system intelligent is its digital signal processing capability for direction of arrival estimation and beam steering. Using direction of arrival algorithms, the system should work out the angle at which all signals arrive at the detectors, be they from the desired user, multipath or interference. Then, the signal from the desired user is identified before steering the beam in the desired user’s direction. Furthermore, the signal environment must be constantly monitored to enhance tracking of the desired user while attenuating the beam in the direction of the unwanted signals.
First, incoming signals are down converted to baseband of intermediate frequencies (IF). This is done by receivers at the output of each array element. Next, the down converted signals are converted into digital format using fast analogue to digital converters (ADCs). Digital signal processors (DSPs) do the weighting of the converted incoming signals. The DSPs process incoming data determining both the amplitude and phase (complex weights) and the multiply these weights with each array element output in order to form the best possible array pattern. This digital beam steering is aimed at minimizing contributions from noise and interference while maximizing the gain in the direction of the desired signal [6]. Several algorithms are used to arrive at these optimum weights.

1.3 Direction of Arrival Estimation Algorithms

Depending on the approach adopted, adaptive algorithms can be categorized as follows. On the basis of the adaptation:

1. Continuous adaptation: These algorithms correct the weights as the incoming data are sampled and continually update them so that they converge at an optimum solution. This strategy is appropriate where the signal statistics vary with time [6]. Examples of algorithms that use this approach are the Least Mean Square (LMS) algorithm, and the Recursive Least square (RLS) algorithm.
1.3.0 Least Mean Square (LMS)

This algorithm is made up of three steps in each recursion, viz. the calculation of the processed signal with the current set of weights, obtaining the error between the desired signal and the processed signal, and the correction of the weights using the obtained error information [7]. The following equations summarize the above three steps.

\begin{align*}
    d(n) &= w_1^*(n)u_1(n) + w_2^*(n)u_2(n) + \cdots + w_t^*(n)u_t(n) \\
    \hat{d}(n) &= w^H(n)u(n) \\
    e(n) &= d(n) - \hat{d}(n) \\
    w(n + 1) &= w(n) + \mu u(n)e^*(n)
\end{align*}

The \( w \) in the above equations is a vector which contains the whole set of weights. The \( H \) in equation (2) denotes the Hermitian transpose of a vector, i.e. the vector is transposed and then each of its elements replaced by its conjugate. At time zero, all weights are initialized to have a value of zero. The symbol \( \mu \) in equation (4) is known as the step size parameter. The value of this parameter influences the both settling time and the steady state error of the LMS algorithm. A large step-size leads to a fast settling but brings about a poor steady state performance. Conversely, a small step-size decreases the steady state error but negatively impacts the rate of convergence. Selecting the current value of this parameter is done by trying out different values in the algorithm.

1.3.1 Recursive Least square (RLS)

Here, the sum of the squares of the errors of different sets of inputs becomes the subject of minimization [7]. The following equations demonstrate how the updating is achieved in each recursion.

\begin{align*}
    k(n) &= \frac{\lambda^{-1}P(n-1)u(n)}{1 + \lambda^{-1}u^H(n)P(n-1)u(n)} \\
    \xi(n) &= d(n) - w^H(n - 1)u(n) \\
    w(n) &= w(n - 1) + k(n)\xi^*(n) \\
    P(n) &= \lambda^{-1}P(n - 1) - \lambda^{-1}k(n)u^H(n)P(n - 1)
\end{align*}

The \( P \) in the above equations is first initialized to \( \delta^{-1} \) where \( \delta \) is a small positive constant and \( I \) is an identity matrix and all \( w \) are again initialized to zeros. The vector \( k \) is a called the Kalman
gain factor while \( \lambda \) is the forgetting factor which is supposed to weight the error value in a different manner depending on the ages of the received signals in a transversal filter.

2. Block adaptation: These algorithms compute the weights based on the estimates obtained from a temporal block of data. This method can be used in a changing environment provided the weights are sporadically computed [6]. An example is the Sample Matrix Inversion (SMI) algorithm.

1.3.2 Sample Matrix Inversion (SMI)

For an \( N \)-element antenna array [7], the baseband received signal vector \( X \) is given by

\[
x(t) = \sum_{i=1}^{M} s_i(k) a_i(\theta_i) + n(k)
\]  

(9)

Where \( x(k) = [x1(k) \ x2(k) \ldots \ xN(k)] \) is a 1 x \( N \) complex valued vector and \( k \) denotes discrete time. The co-channel transmitted signals are represented by, \( s_i(k) \) for \( i = 1,2,\ldots \ldots \ldots M \). The 1 x \( N \) row vector \( a_i \) is the array response vector associated with the \( i^{th} \) transmitted signal, which models the antenna array gain and phase across each of the elements. This is a function of the angle of arrival, \( \theta_i \) of the received signal. The noise, on the other hand, is modeled by \( n(k) = [n1(k) n2(k) \ldots \ldots nN(k)] \), another 1 x \( N \) vector of complex white noise with variance \( \sigma_n^2 \). We are assuming that each of the transmitted signals and noise sequences are mutually uncorrelated. The sensor outputs are each multiplied by a complex weight which may vary with time, and then summed to produce the output. The goal is to adjust the complex weights to improve reception of the signal of interest (SOI). The array output is expressed as

\[
y(k) = \sum_{i=1}^{N} w_i(k)x_i(k) = x(k)w(k)
\]  

(10)

Where \( w(k) \) is the \( N \) x 1 column vector of beamformer weights. The weight vector that minimizes the mean square error is given by

\[
w_{opt} = R^{-1}P
\]  

(11)

Where \( R = E[xn(k)x(k)] \) and \( P = E[xn(k)d(k)] \). The SMI [2,3] method is a technique used to approximate the solution to the minimum mean square error (MMSE) problem. It assumes that there is a known training sequence \( d(k) \) which occurs in the SOI data, that for some \( j \) and \( k \).

First, \( K \) samples of the signal vector \( X \) are collected in a \( K \) x \( N \) matrix as shown below
This sample is obtain an estimate of the $N \times N$ covariance matrix given by

$$X_K(k) = \begin{bmatrix} x_1(k) & \cdots & x_N(k) \\ \vdots & \ddots & \vdots \\ x_1(k+K-1) & \cdots & x_N(k+K-1) \end{bmatrix}$$  \hspace{1cm} (12)

And an $N \times 1$ cross-covariance vector given by

$$\hat{P}(k) = X_K^H(k)d(k)$$  \hspace{1cm} (13)

Where $d(k) = [d(k)d(k+1)\ldots d(k+K-1)]$ is a $K \times 1$ column vector. The approximation to the solution of MMSE problem becomes

$$\hat{\omega}(k) = \hat{R}(k)^{-1}\hat{P}(k)$$  \hspace{1cm} (15)

SMI adaptation has poor performance so far as interference cancellation goes. This is imputed to the inadequate estimate of $R$ and $P$ using a finite size $K$ block of array data. Furthermore, in a scenario where signals are not continuously transmitted, the problem of partial burst overlap of interferers further degrades SMI performance.

On the basis of the information required we have:

1. Reference signal based algorithms: They are based on minimization of the mean square error between the received and the reference signals. This demands that a reference signal be made available which has a high correlation with the desired signal [6]. Examples include the Least Mean Square (LMS) algorithm, the Recursive Least square (RLS) algorithm, and the Sample Matrix Inversion (SMI) algorithm.

2. Blind adaptive algorithms: These generate the required reference signal from the received signal to obtain the desired signal. An example is the Constant Modulus Algorithm (CMA).

1.3.3 Constant Modulus Algorithm (CMA)

This algorithm consists of three steps in each recursion [7]. These are: the calculation of the processed signal with the current set of weights, then error generation, and lastly, the correction of the weights using the obtained error information. The following equations summarize the above three steps.
In equation (16), $W$ denotes weight vector of the arrays. In equation (17), $e(k)$ is the error at $k$ iteration. The symbol $\mu$ in equation (18) is known as the step size parameter. The value of this parameter influences both the settling time and the steady state error of this algorithm.

### 2. PATCH ANTENNA DESIGN

There have been a lot of advancements in wireless body area networks (WBANs) which have led to the incorporation of conformal radiating systems. Today, WBAN applications find use in diverse fields from medical telemetry, military, emergency response, to sports and personal entertainment. An important feature that must be considered in the design is low power consumption [8]. In order to allow a user to go about their usual activities with minimal discomfort or limitations, a body-worn textile array system provides a practical way to deploy a WBAN for medical telemetry applications.

For a while now, body-worn health monitoring systems have been in use. For example, the smart shirt, clothes for teleassistance in medicine project, the European Wearable Healthcare System (WEALTHY) [9], and the in-shoe-plantar pressure measurement system [10]. These health monitoring systems perform several functions such as electrocardiography and temperature monitoring as well as conveying this information to health personnel via preexisting telecommunication technology, for instance the global system for mobile communication (GSM) [8]. Without such communication, telemetry would be rendered impossible.

The fabrication of textile antenna uses flexible materials which are either conductive or non-conductive. The estimation of the initial dimensions of the microstrip antenna patch is done by following a known procedure detailed in [11]. To achieve a circular polarization, a diagonally fed probe and a pair of chamfered edges are diagonally positioned at opposite ends of the patch. The array radiating elements are secured on both sides of a nonconductive substrate (Cordura) with a thickness of 4mm. Cordura, made from high tenacity polyamide fibres, is chosen because
of its constant thickness and its high resistance ensuring that the patch antenna geometry will be more or less stable. Through measurements, Cordura has been found to have a relative permittivity, $\varepsilon_r = 1.9$ and a loss tangent, $\delta = 0.0098$ at 2.6GHz [12]. Cordura does not absorb water which helps in keeping its relative permittivity constant.

The radiating patch and ground are made from a conductive fabric, ShieldIt Super from LessEMF of conductivity $6.67e+005$ S/m. It is made of polyester substrate conductive nickel and copper plated then backed with nonconductive hot melt adhesive. It has good properties such as excellent shielding and low corrosion. It is also easy to cut and sew. Furthermore, its adhesiveness is activated at $130^0$ C. It can be ironed on to cotton or another fabric [13]. The bandwidth and efficiency performance of a planar microstrip antenna is mainly determined by the substrate dielectric constant and its thickness.

For a patch antenna of a resonating frequency of 2.45GHz, the following measurements (all in mm) were found to be suitable:

- Ground/Substrate length and width, $L_g=W_g=58$
- Patch length and width, $L_p=W_p=40$
- Aperture length and width, $L_s=W_s=10$
- Ground/Patch thickness, $h_p=0.17$
- Substrate thickness, $h_{sb}=4$
- Truncation on the patch for circular polarization, $t_p=5$
- Feed position, $(x_f,y_f)=(8,8)$

Figure 2.0 below shows the patch antenna as it appears in CST Microwave Studio, the software used in the design and simulation of the antenna.
In Figure 2.1 below, the red dot on the patch antenna represents the port.

3. SIMULATION AND RESULTS

The return loss simulation results are shown below:
Figure 3.0 The resonant frequency is found to be 2.4454 GHz

Figure 3.1 The -10dB bandwidth is 89.7 MHz
Figure 3.2 3-D farfield characteristics

Figure 3.3 Polar farfield characteristics
Given that the patch antenna is made of flexible materials, it was also important to find out how the resonant frequency and the return loss were affected under various bent conditions. The simulations were done for various radii (R in mm) of bending around the vertical (y) axis.

The return loss and farfield directivity results were as follows.

a. **R=200**

![Figure 3.5.0 Return loss with R=200](image)

Figure 3.5.0 Return loss with R=200
Figure 3.5.1 Farfield directivity with $R=200$

![Farfield directivity with $R=200$](image)

b. $R=100$

Figure 3.6.0 Return loss with $R=100$

![Return loss with $R=100$](image)

Figure 3.6.1 Farfield directivity with $R=100$

![Farfield directivity with $R=100$](image)
c. **R=80**

![Figure 3.7.0 Return loss with R=80](image)

Figure 3.7.1 Farfield directivity with R=80

**d. R=50**

![Figure 3.8.0 Return loss with R=50](image)

18
Figure 3.8.1 Farfield directivity with R=50

Figure 3.9.0 Return loss with R=30

Figure 3.9.1 Farfield directivity with R=30

e. **R=30**
3.0 Summary Results of Bending Antenna

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>Resonant Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2.4278</td>
</tr>
<tr>
<td>100</td>
<td>2.4412</td>
</tr>
<tr>
<td>80</td>
<td>2.4304</td>
</tr>
<tr>
<td>50</td>
<td>2.4237</td>
</tr>
<tr>
<td>30</td>
<td>2.4278</td>
</tr>
<tr>
<td>20</td>
<td>2.4247</td>
</tr>
</tbody>
</table>

Table 1 Summary results of bending antenna
In the simulations, discrete port is used for excitation because of ease of simulation; otherwise, there are expected variations in real life patch antenna performance.

### 3.1 Patch Antenna and Human Body Interactions

There is increased energy absorption in biological tissues which suggests that the human body will have even greater influence on the nearby antenna’s performance. But despite much higher tissue losses at 2.45 GHz, the performance of the antenna can turn out to be good in this band, especially when the antenna-body spacing is $\lambda/8$ or more. The table below shows the electromagnetic properties of the human body tissues at 2.45 GHz [14].

<table>
<thead>
<tr>
<th>Tissue Name</th>
<th>Conductivity [S/m]</th>
<th>Relative Permittivity</th>
<th>Loss Tangent</th>
<th>Penetration Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>1.467</td>
<td>42.47</td>
<td>0.24837</td>
<td>0.023761</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.69816</td>
<td>17.975</td>
<td>0.27927</td>
<td>0.032545</td>
</tr>
<tr>
<td>Blood</td>
<td>2.5878</td>
<td>58.181</td>
<td>0.31981</td>
<td>0.015842</td>
</tr>
<tr>
<td>Bone, Cancellous</td>
<td>0.82286</td>
<td>18.491</td>
<td>0.31996</td>
<td>0.028087</td>
</tr>
<tr>
<td>Bone, Cortical</td>
<td>0.40411</td>
<td>11.352</td>
<td>0.25597</td>
<td>0.044616</td>
</tr>
<tr>
<td>Brain, Gray Matter</td>
<td>1.843</td>
<td>48.83</td>
<td>0.27137</td>
<td>0.02031</td>
</tr>
<tr>
<td>Breast Fat</td>
<td>0.14067</td>
<td>5.137</td>
<td>0.1969</td>
<td>0.085942</td>
</tr>
<tr>
<td>Cartilage</td>
<td>1.7949</td>
<td>38.663</td>
<td>0.3338</td>
<td>0.018638</td>
</tr>
<tr>
<td>Cerebro Spinal Fluid</td>
<td>3.5041</td>
<td>66.168</td>
<td>0.38078</td>
<td>0.012537</td>
</tr>
<tr>
<td>Cornea</td>
<td>2.3325</td>
<td>51.533</td>
<td>0.32544</td>
<td>0.016548</td>
</tr>
<tr>
<td>Eye Sclera</td>
<td>2.0702</td>
<td>52.558</td>
<td>0.28321</td>
<td>0.018773</td>
</tr>
<tr>
<td>Fat</td>
<td>0.10672</td>
<td>5.2749</td>
<td>0.14547</td>
<td>0.11455</td>
</tr>
<tr>
<td>Gall Bladder Bile</td>
<td>2.8447</td>
<td>68.305</td>
<td>0.29945</td>
<td>0.015592</td>
</tr>
<tr>
<td>Heart</td>
<td>2.2968</td>
<td>54.711</td>
<td>0.30185</td>
<td>0.017286</td>
</tr>
<tr>
<td>Kidney</td>
<td>2.4694</td>
<td>52.63</td>
<td>0.33736</td>
<td>0.015811</td>
</tr>
<tr>
<td>Liver</td>
<td>1.7198</td>
<td>42.952</td>
<td>0.2879</td>
<td>0.020434</td>
</tr>
<tr>
<td>Lung, Inflated</td>
<td>0.81828</td>
<td>20.444</td>
<td>0.28779</td>
<td>0.02963</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.773</td>
<td>52.668</td>
<td>0.24205</td>
<td>0.021886</td>
</tr>
<tr>
<td>Skin, Dry</td>
<td>1.4876</td>
<td>37.952</td>
<td>0.28184</td>
<td>0.022198</td>
</tr>
<tr>
<td>Skin, Wet</td>
<td>23.984</td>
<td>20.369</td>
<td>0.84665</td>
<td>0.0010736</td>
</tr>
<tr>
<td>Small Intestine</td>
<td>3.2132</td>
<td>54.324</td>
<td>0.42529</td>
<td>0.012438</td>
</tr>
<tr>
<td>Stomach</td>
<td>2.2546</td>
<td>62.078</td>
<td>0.26114</td>
<td>0.018707</td>
</tr>
<tr>
<td>Testis</td>
<td>2.2084</td>
<td>57.472</td>
<td>0.27628</td>
<td>0.018394</td>
</tr>
<tr>
<td>Tongue</td>
<td>1.8396</td>
<td>52.558</td>
<td>0.25167</td>
<td>0.021083</td>
</tr>
</tbody>
</table>

Table 2 Electromagnetic properties of the human body tissues at 2.45 GHz
3.2 The Specific Absorption Rate (SAR)

The other thing we want to consider is the amount of heat generated in the tissue in the vicinity of an antenna. This is measured as specific absorption rate (SAR) in watts per kilogram (W/kg). Usually, it is taken as an average value over a certain cubic volume of mass. Various countries have differing rules on how to calculate SAR and its limits. Typical limits amount to 1.6W/kg for a volume 1g of mass as has been set by the FCC for the U.S. while 2W/kg for a volume of 10g is the limit set by the European Union [14].

I was not able to carry out the investigation of the effects of the patch antenna on human body models for lack of the required CST Microwave Studio licenses.

4. DIGITAL BEAMFORMING SYSTEM

4.0 Implementation of the Digital Beamforming System

Once the patch antennas have been investigated and their performance found to be satisfactory, the next step is implementing the digital beamforming system. The receiver system receives the output signals, filters and down converts this signal to a 20-MHz intermediate frequency (IF) signal. An ADC is used to sample the IF signal. A phase-locked loop (PLL) can be used as a local oscillator (LO) to generate sine waves for down-conversion mixer in the receiver system. This in turn generates a continuous wave (CW) signal at the required 2.45GHz under the control of a field programmable gate array (FPGA) board.

The actual digital beamforming can be implemented in FPGA. This has the full digital demodulation path for data communications which employs high-speed parallel programmable components. These include digital quadrature mixer, digital wave synthesis, and cyclic redundancy check-finite impulse response (CRC/FIR) decimation filter. These digital function blocks are interconnected using an advanced extensible interface bus which is then mastered by an embedded central processing unit (CPU). The collected data can be used to perform direction of arrival (DOA) estimation using an appropriate algorithm in a computer-controlled demonstrator, for example [8].
5. CONCLUSION

Due to time constraints the actual design of the patch antenna as well as the implementation of the actual digital beamforming system were not done and therefore no comparisons can be made between the simulation results and the experimental ones. The simulation of the digital beamforming system was also not possible due to lack of FPGA boards or DSPs.

5.0 Looking into the Future

Future work should focus on miniaturizing the digital beamforming system in order to make it portable and inconspicuous. We are looking into a future that has ubiquitous wireless computing.
REFERENCES


