

Inertial Control of a Beamforming Antenna Array for Use in Cellular Phones

by
Patrick Schmidt

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1 INTRODUCTION

1.1 MOTIVATION

Recently in the news more questions have been raised about the safety of long term cellular phone use and a possible connection with brain cancer due to the absorption of electromagnetic radiation energy [1]. Unfortunately, a confident conclusion about the effects of mobile phone use may still be years away. This is due to the fact that these effects are difficult to measure. Studies cited in the news up to now have relied on methods whose legitimacy are often questioned—such as asking a patient that has already been diagnosed with brain cancer to estimate their past phone use. A conclusive study would require large test and control populations, an objective means of measuring phone use that does not rely on how the subjects *feel* about their past phone usage and a long period of time over which to take measurements. Moreover, a conclusive study would need a means of separating the effects of electromagnetic radiation from other phenomena such as the low intensity thermal radiation, which is also given off by all cellular phones. This report assumes that, once the verdict is in, there will in fact be a need to reduce electromagnetic radiation exposure; and a method for reducing this exposure is presented.

1.2 TOPIC

Currently, to improve reception, the design of cellular phone antennas seeks to make radiation characteristics as omnidirectional as possible. In this report, a beamforming array of microstrip patch antennas, designed in [2], is used to direct radiation away from the user [2]. Beamforming is the practice of transmitting/receiving the same information

over multiple antennas (the array), while varying the phase, amplitude, and/or spatial location of the individual antennas (elements) with the intention that radiation from the elements will sum constructively in a desired direction, and sum destructively (or cancel) in other directions. In the present application, beamforming will only be effective if the phone knows which way to direct (scan) the beam. If the phone cannot estimate the proper beam direction effectively, the system may expose the user to *more* radiation than a typical omnidirectional antenna.

Beamforming alone, therefore, does not tell the whole story. The phone must also track its own position and orientation with respect to the user so that it can determine the best direction to form the beam. The main purpose of this report is to suggest and test an algorithm to control the antenna array. The inputs to the array control algorithm are integrated accelerometers, which already come in most new Smartphones. The final algorithm is a simple inertial navigation system (INS) with zero-motion detection. For readers familiar with navigation, INS is an advanced electronic form of dead reckoning that accounts for rotation in addition to translation. For readers new to INS, the complete derivation is the topic of chapter 2. In short, inertial navigation works by detecting acceleration and rotation, and then calculates a position by a series of integrals and rotational transforms.

1.3 THE BASIC MEMS ACCELEROMETER

As mentioned in the section 1.2, most new Smartphones come with integrated accelerometers. More specifically, these are Micro Electrical Machine System (MEMS) accelerometers. These tiny devices have been around for decades [3] but were launched out of specialized applications and into the mainstream by their use in Nintendo Wii controllers in 2006.

Before the development of MEMS technology, accelerometers were only available in bulky, sensitive and high power packages. The proliferation of MEMS in the 1990's and 2000's has brought many exotic technologies to the domain of inexpensive mass production and miniaturization. Unlike microprocessors and other semiconductors, which work exclusively by the transport of electrons, MEMS devices have moving parts. MEMS feature sizes range from a few to hundreds of microns [5]. Fig. 1.3.1, which shows a mite next to a MEMS device, provides a good size comparison [6].

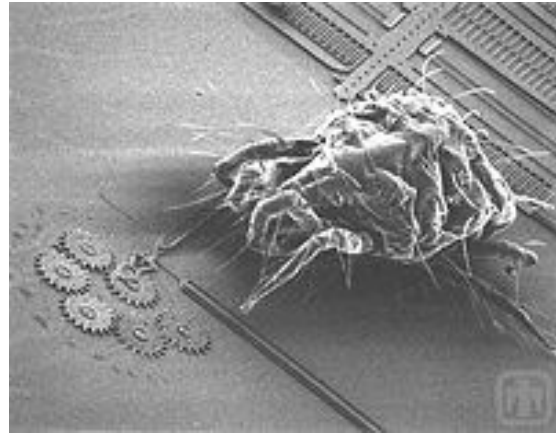


Figure 1.3.1 Mite next to a MEMS device.

MEMS accelerometers, in particular, consist of a structure suspended by springs which provide resistance to motion. Deflection of the suspended structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the spring suspended structure. Measurements of the differential capacitor voltage provides a value that is proportional to the acceleration of the device [7]. The accelerometers are designed such that acceleration is measured only along a single axis. Most MEMS accelerometer devices include two or three orthogonally oriented single-axis accelerometers in the same chip. Single-axis accelerometers have limited use, and are much harder to find than two- or three-axis accelerometers. In this paper, "accelerometer," may refer to a single axis of a three-axis accelerometer, or an entire three-orthogonally-oriented accelerometer package, depending on context.

Since the three axes are orthogonal, the accelerometer's measurements give a complete description of the force experienced by the device at any instant. Fig. 1.3.2 shows an example of a typical accelerometer package and axis orientations [7].

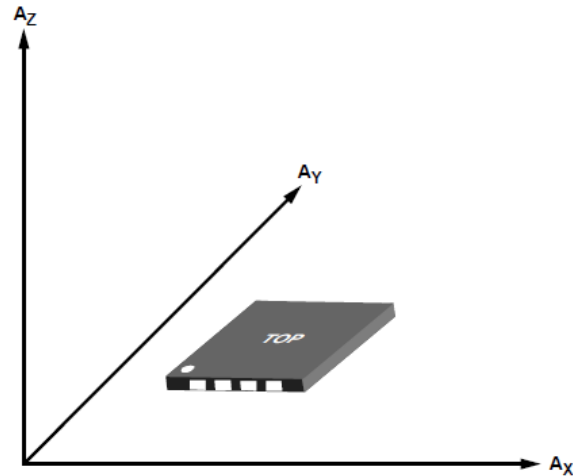


Figure 1.3.2 MEMS 3-axis accelerometer package with axis orientations shown.

1.4 WHY IS AN INS ALGORITHM NECESSARY?

MEMS accelerometers also detect the force of gravity (g), and in fact, their output values are usually given in multiples of g . For example, if the accelerometer of Fig. 1.3.2 were lying stationary on a table, the output of the device would be: $A_x = 0$, $A_y = 0$, $A_z = -1$. While stationary, the magnitude of the three outputs is always $1g$, even though the vector $\vec{A} = [A_x \ A_y \ A_z]^T$ may point in any direction. The acceleration reported by each axis is the dot product of that axis' basis vector and the true acceleration. Equation (1.4.1) and Fig. 1.4.1 show this relationship.

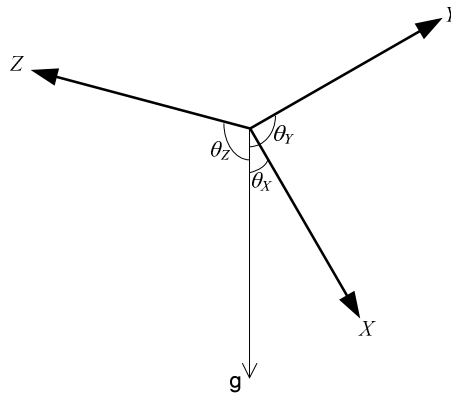


Figure 1.4.1 Gravity (g) shown with the angles between each measurement axis and itself.

In (1.4.1), $\mathbf{e}_i$ are the basis vectors representing the coordinate axes, and θ_i is the smaller of the two angles between $\mathbf{e}_i$ and $\mathbf{g}$.

$$A_i = \mathbf{e}_i \cdot \mathbf{g} = \|\mathbf{e}_i\| \|\mathbf{g}\| \cos(\theta_i), \quad i \in x, y, z \quad (1.4.1)$$

Noting that the magnitudes of both $\mathbf{e}_i$ and $\mathbf{g}$ are one, the angles θ_x , θ_y , θ_z can be calculated.

$$\theta_i = \arccos(A_i), \quad i \in x, y, z \quad (1.4.2)$$

This simple calculation looks promising for finding the orientation of the accelerometer, but unfortunately the inputs and outputs are not unique to the orientation shown. Consider the case when the orientation of Fig. 1.4.1 is rotated any angle about the g axis. Clearly, the accelerometer outputs will not change. This fact is particularly damaging to the hope for a very simple solution to finding the phone's orientation. Rotation about the axis of gravity is key, because errors in this calculation quickly result in forming the radio beam directly at the user, rather than away from them. It is for this reason that a true inertial navigation algorithm is necessary.

3.5 MODEL VERIFICATION / PERFORMANCE

With a model in hand, the next logical step is to test the performance of this system. Specifically, one cannot expect such a model to function indefinitely because discrete integrators introduce accumulating error to the system. The nonlinear feedback also introduces error because this block always operates with a one sample delay. In the remainder of this chapter, the INS will be used to simulate a few test motions to confirm functionality.

3.6 FRAME ORIENTATION AND ACCELEROMETER ARRANGEMENT

Before actually running simulations to see if the INS model works, it will be useful to define some quantities and references for the phone, user and INS. One issue of particular importance is the arrangement of the accelerometers in the phone. For the system to be functional, matrix $\underline{J}$ must have rank six, so that $\underline{Q}$ exists. The merits of different numbers and configurations of accelerometers will be assessed later. For now, an intuitive and symmetric arrangement of four three-axis accelerometers at each of the four corners of the phone will be used to check that the tracking algorithm works. Fig. 3.6.1(a) shows this configuration, where the numbers 1, 2, 3, and 4 represent three-axis accelerometers one through four.

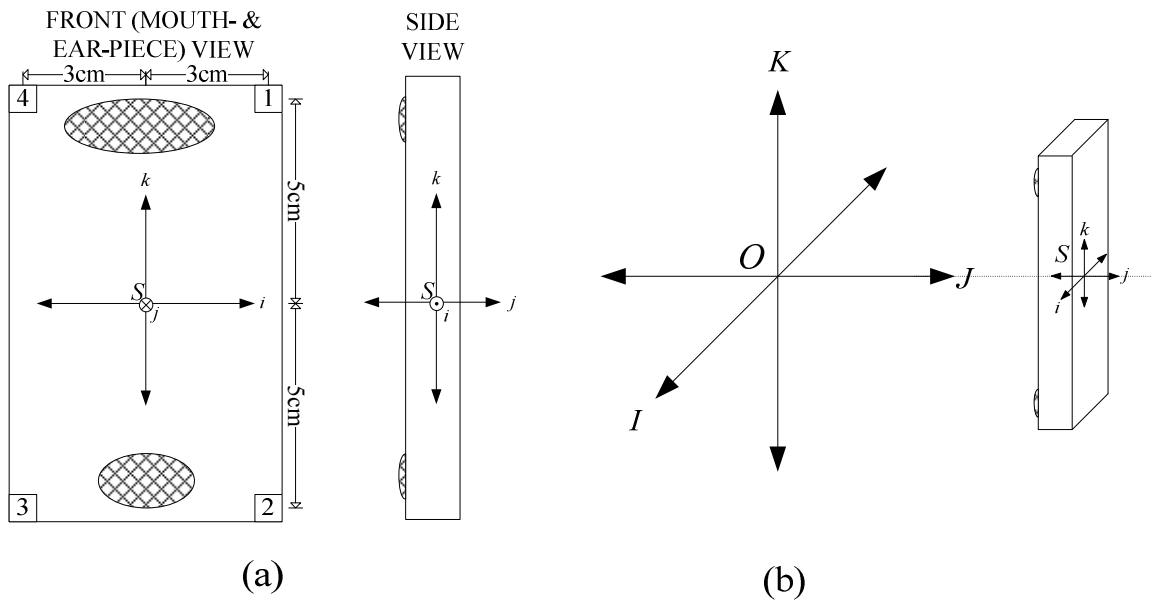


Figure 3.6.1 (a) Orientation of S within the phone. (b) Orientation of the phone and S with respect to the inertial frame O .

In addition to the accelerometer arrangement, Fig. 3.6.1(a) and (b) show how frame O and S are oriented with respect to each other. Fig. 3.6.1(a) shows the orientation of S in the phone, which is considered to be in an un-rotated state when the basis vectors $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$, are parallel to the inertial frame's basis vectors $\mathbf{I}$, $\mathbf{J}$, $\mathbf{K}$, respectively. Fig. 3.6.1(b) shows one example of the phone in an un-rotated state. Furthermore, the origin of O will always be assumed to be located at the center of the user's head. With the user's head located at the center of O , Fig. 3.6.1(b) could correspond to a left-handed user looking in the $+\mathbf{I}$ direction holding the phone upright to their left ear. On the other hand—no pun intended—a user is looking in the $-\mathbf{I}$ direction would be holding the phone with their right hand.

Besides considering the orientations of O and S with respect to each other, each of the four accelerometers has three axes that must be specified. The orientation of the accelerometers within S is specified by the vector $\boldsymbol{\theta}_{B,A}$ from chapter 3. Since a three-axis

accelerometer forms an orthonormal basis for measuring acceleration, any orientation of accelerometers provides a complete set of information. Strange orientations, however, confer no advantage and complicate computation of the dot product in (2.6.1). For this reason, accelerometers will be oriented with axes parallel to the axes of S , so that the x-axis of all accelerometers is parallel to $\mathbf{i}$, the y-axis of all accelerometers is parallel to $\mathbf{j}$, and the z-axis of all accelerometers is parallel to $\mathbf{k}$.

3.7 TESTING THE TRACKING ALGORITHM

3.7.1 TEST MOTION 1—A SIMPLE ORBIT

With the orientation and placement of the accelerometers and frames specified, a test of the tracking algorithm can be performed. In the first test, the phone orbits the origin of O in the xy -plane at a distance of 0.1 meters. During the same time, the phone rotates about the $\mathbf{k}$ axis such that the same face of the phone is always presented to the origin of O . This is the same motion that the moon has as it rotates about the earth. The phone completes one orbit every four seconds and the test is run for 10 seconds. Fig. 3.7.1.1 shows a diagram of this test's motion.

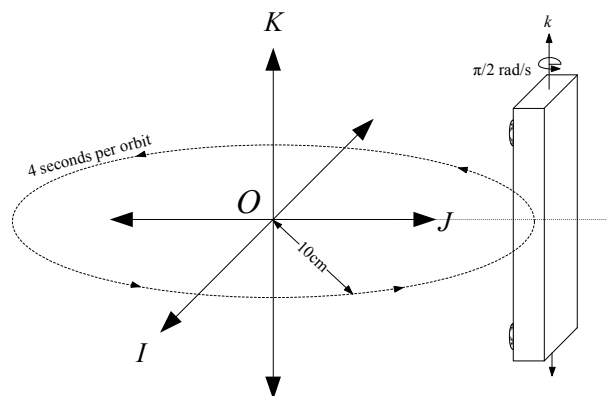


Figure 3.7.1.1 Simple orbit motion

Lastly, substitution of (7.3.9) into (7.3.7) gives

$$dp = dx \sin(\theta) \cos(\phi). \quad (6.3.10)$$

Multiplication by the wave number will then give dp in radians, and matches (6.3.4). The derivation for (6.3.5) would proceed in a similar fashion.

6.4 SCANNING

Scanning is the process of varying the amplitude, phase, or geometry of an array in order to point the main beam in a certain direction. From (6.3.2), the array will have its maximum when both Ψ_x and Ψ_y are zero. β_x and β_y , the progressive phase shifts of the element in the x and y directions, are adjustable; therefore, a user may point the radio beam in a particular direction θ_0, ϕ_0 , by solving for β_x and β_y with Ψ_x and Ψ_y equal to zero. Solving (6.3.4) and (6.3.5) for β_x and β_y gives

$$\beta_x = -kd_x \sin(\theta_0) \cos(\phi_0), \quad (6.4.1)$$

and

$$\beta_y = -kd_y \sin(\theta_0) \cos(\phi_0), \quad (6.4.2)$$

which are the phase shifts required to direct the radio beam in direction θ_0, ϕ_0 .

6.5 PLANAR ARRAY SCANNING EXAMPLE

To demonstrate the effectiveness of the uniform planar scanning array, three sample radiation patterns are shown below for an isotropic source and an array with four elements in the y direction and three elements in the x direction (a four by three array is the one designed in [2]). In Fig. 6.5.1, the rectangle at the origin plane of the array; no phase shift is applied, so the array's main beam is directed completely in the z directions. The field is symmetric about the plane of the array because no information was given about what type of object the array is resting on, if any. Without such specification, the uniform array looks identical both from above and underneath. In the same way, if one were to draw uniformly spaced dots on a transparency paper, it would be impossible for viewers to determine which side of the transparency was the "top", and which was the "bottom". Fig. 6.5.2 shows the system with a $\theta=45^\circ$, $\phi=30^\circ$ scan.

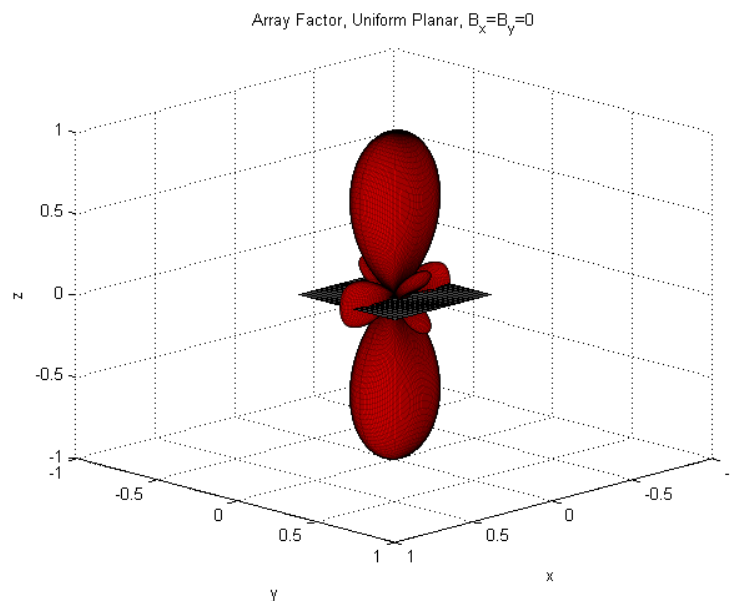


Figure 6.5.1 Vertical array pattern with no progressive phase shift.

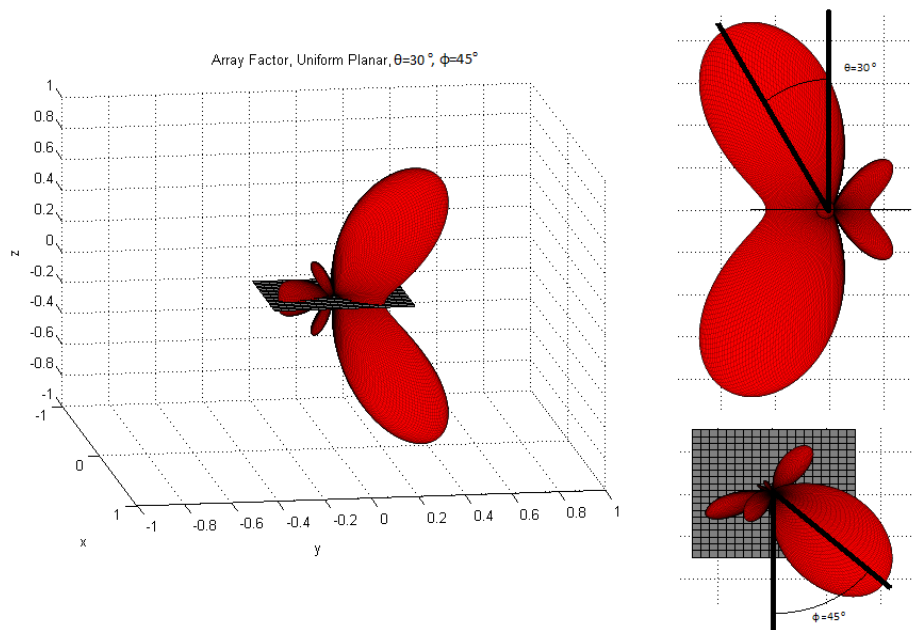


Figure 6.5.2 Same array as in Fig. 6.5.1, but with nonzero progressive phase shifts that combine to scan the main beam to $\theta=30^\circ$ and $\phi=45^\circ$.

6.6 USING ASYMETRIC ELEMENTS

The symmetry about the xy-plane seen in Fig. 6.5.1 and Fig. 6.5.2 is totally undesired. The rectangle shown at the origin in these examples will ultimately represent the back of a cellular phone, therefore, it is required that the bulk of the radiation is present only on one side of this rectangle. To achieve this, the array designed specifically for this application by [2], which uses microstrip patch antennas, is used. Unlike the isotropic sources used in sections 6.2 to 6.5, microstrip patch antennas have the useful property that they transmit negligible power behind the plane of the array. The radiation pattern for a patch antenna source shown below in Fig. 6.6.1. Notice that the field radiation does not extend behind the plane. One objection to this pattern might be the obvious discontinuities at the plane surface in the figure. The pattern shown is a first order approximation. Real microstrip patch antennas have a negligibly small amount of far field radiation behind the array plane. The bigger inaccuracy in this approximation arises

in showing that the field touches the plane and then abruptly stops. In fact, the field diminishes asymptotically as it approaches the plane so that the field doesn't actually touch the plane. For testing the effectiveness of the INS to mitigate radiation exposure, the first order approximation is quite effective.

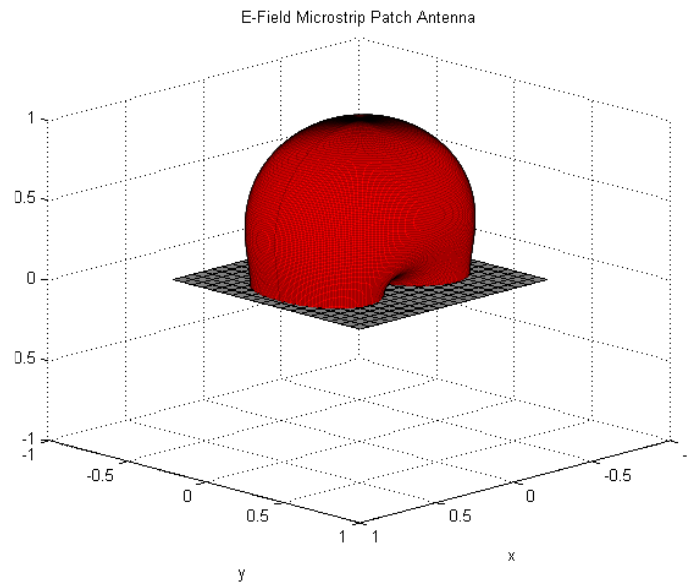


Figure 6.6.1 First order approximation of a microstrip patch antenna.

Returning to (6.3.2), the first factor in the product is replaced by the electric field of a microstrip patch antenna E_{MSP} , so that (6.3.2) becomes

$$E_{PLANAR} = E_{MSP} \left[\frac{\sin\left(\frac{M}{2}\psi_x\right)}{\sin\left(\frac{1}{2}\psi_x\right)} \right] \left[\frac{\sin\left(\frac{N}{2}\psi_y\right)}{\sin\left(\frac{1}{2}\psi_y\right)} \right]. \quad (6.6.1)$$

The new radiation patterns are shown in Fig. 6.6.2

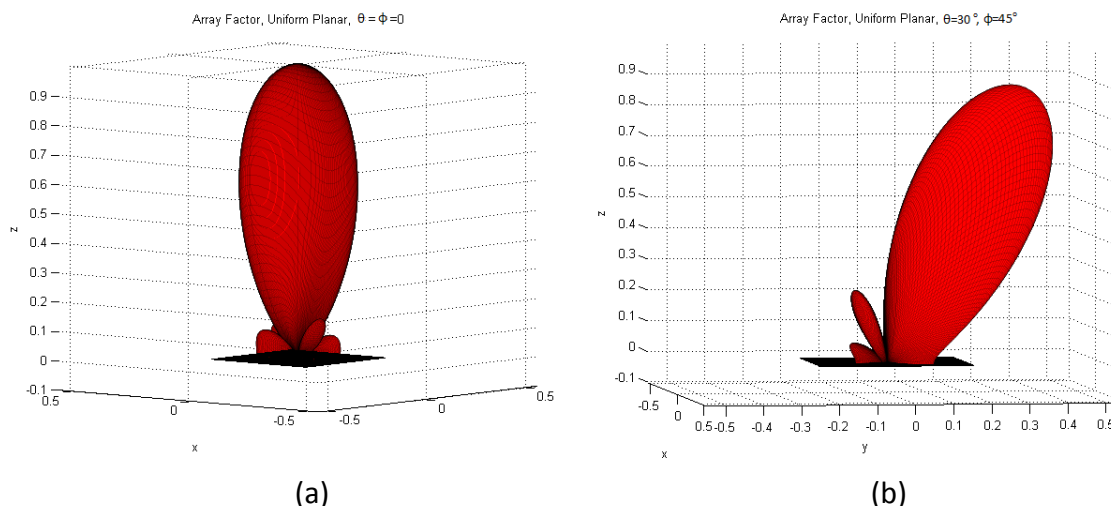


Figure 6.6.2 Examples of beamforming with microstrip patch antennas. (a) No progressive phase. (b) Scanned to $\theta=30^\circ$ and $\phi=45^\circ$.

6.7 BINOMIAL ARRAY EXCITATION

Before moving on to the task of connecting the array to the INS, one other type of array ought to be considered in testing: binomial excitation. Binomial arrays have the distinct property that, for low scan angles, they do not have sidelobes, which may prove to be very desirable in protecting users from radiation. In binomial excitation, the relative amplitudes of successive elements are distributed according to a binomial tree, the first six rows of which are shown below in Fig. 6.7.1

m	Relative Element Amplitudes						
1				1			
2				1	1		
3			1	2		1	
4		1	3	3		1	
5	1	4	6		4		1
6	1	5	10	10	5		1

Figure 6.7.1 Relative element to element amplitudes for a binomially excited linear array.

To find an AF and total field for a binomial planar array, one must first return to (6.2.6), which is repeated below.

$$E_{\text{LINEAR}} = E_{\text{ELEMENT}} \left(A_0 e^{j\theta_0} + A_1 e^{j(kd \cos(\theta) + \theta_1)} + \dots + A_M e^{j(kM d \cos(\theta) + \theta_M)} \right) \quad (6.2.6)$$

From [2], there are three elements in the x direction, and four elements in the y direction, these correspond to the linear array factors seen in (6.7.1) and (6.7.2) below.

$$AF_{\text{xLINEAR}} = e^{j\theta_0} + 2e^{j(kd \cos(\theta) + \theta_1)} + e^{j(k2d \cos(\theta) + \theta_2)} \quad (6.7.1)$$

$$AF_{\text{yLINEAR}} = e^{j\theta_0} + 3e^{j(kd \cos(\theta) + \theta_1)} + 3e^{j(k2d \cos(\theta) + \theta_2)} + e^{j(k3d \cos(\theta) + \theta_2)} \quad (6.7.2)$$

Using the progressive phase requirement (i.e. $\theta_i = i \cdot \beta$), one can rewrite (6.7.1) and (6.7.2) as

$$AF_{\text{xLINEAR}} = 1 + 2e^{j(kd \cos(\theta) + \beta_x)} + e^{j2(kd \cos(\theta) + \beta_x)}, \quad (6.7.1)$$

and,

$$AF_{\text{yLINEAR}} = 1 + 3e^{j(kd \cos(\theta) + \beta_y)} + 3e^{j2(kd \cos(\theta) + \beta_y)} + e^{j3(kd \cos(\theta) + \beta_y)} \quad (6.7.2)$$

The planar field, according to (6.3.2), is now

$$E_{\text{PLANAR}} = E_{\text{MSP}} AF_{\text{xLINEAR}} AF_{\text{yLINEAR}} \quad (6.7.3)$$

Because the progressive phase shift is defined in the same way as in section 6.3, the binomial array can be scanned using (6.4.1) and (6.4.2). For comparison, the radiation patterns with the scan angles of Fig. 6.6.2 are repeated using a binomially excited array and shown in Fig. 6.7.2. The two main differences between the uniform and binomial excitation are the lack of prominent sidelobes with binomial excitation and noticeably wider beamwidths.

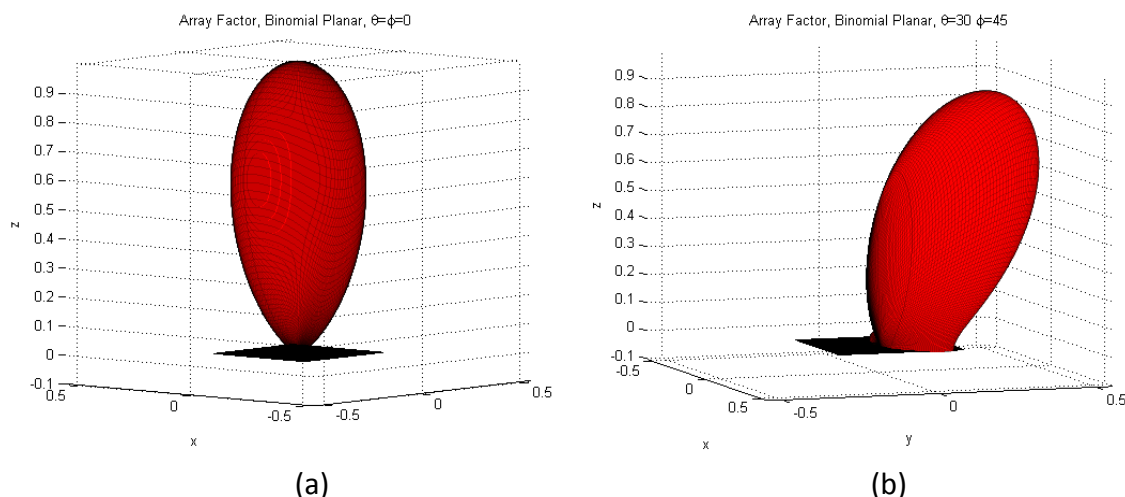


Figure 6.7.2 Examples of beamforming with microstrip patch antennas and binomially excited elements. (a) No progressive phase. (b) Scanned to $\theta=30^\circ$ and $\phi=45^\circ$. A small sidelobe can be seen protruding from behind the mainlobe in (b).

6.8 ATTACHING THE ARRAY TO THE INS

With a functional array and microstrip patch design, the INS can be married to a controller that calculates the necessary progressive phase shifts, β_x and β_y , which will direct radiation away from unsuspecting users. In the following sections, the INS will be expanded to its final form—a system that takes accelerometer sensor inputs and returns the progressive phase shifts required to direct the radio beam in an optimal direction.

In Fig. 6.3.1 the antenna array was laid out on the xy-plane, but in implementation the array will be in the xz-plane, affixed to the back of the phone, as shown in Fig 6.8.1. The patch array designed in [2] has four elements in the vertical (z) direction and three elements in the horizontal (x) direction.

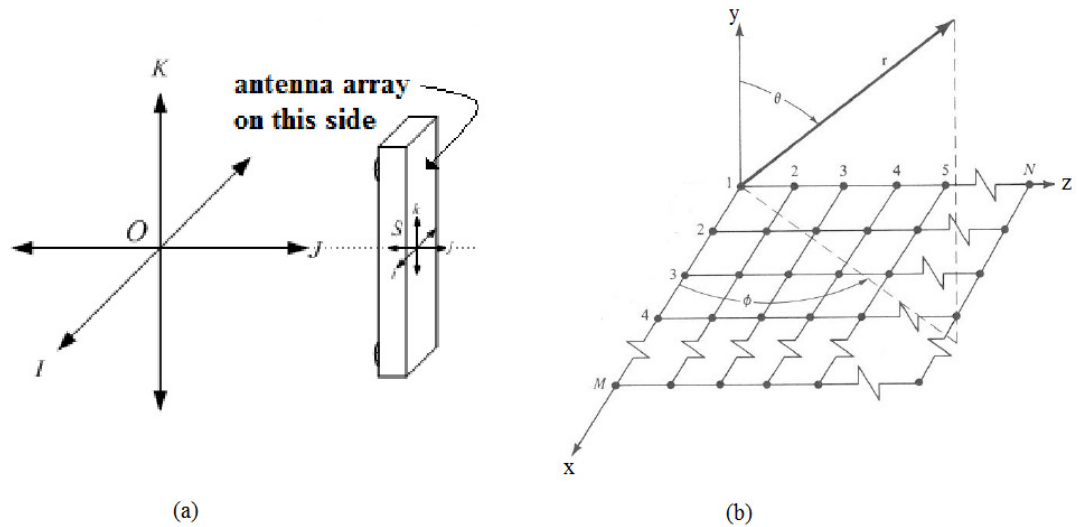


Figure 6.8.1 (a) Antenna array location. (b) Antenna array orientation.

6.9 POINTING THE BEAM

The vector $\mathbf{r}$ shown in Fig. 6.8.1(b) represents the desired beam direction provided by the INS. This vector is simply vector $\mathbf{r}_{A,S}$ from chapter 2. Fig. 6.9.1 shows this fact: by simply attaching $\mathbf{r}_A$ to the origin of S, one has a vector that points away from the user. Unfortunately, however, $\mathbf{r}_A$ is in the coordinates of O, while the array, because it is fixed to the back of the phone, is defined in frame S. Using $\underline{\mathbf{F}}$ from the INS, one can rotate $\mathbf{r}_A$ back into the coordinates of S. After this rotation is made, the geometry of the system is now identical to the geometry shown in Fig. 6.8.1(b), so that angles θ and ϕ are easily calculated as,

$$\theta = \arccos \left(\frac{\mathbf{r}_{y,A,S}}{\|\mathbf{r}_{A,S}\|} \right) \quad (6.9.1)$$

and,

$$\phi = \arctan \left(\frac{\mathbf{r}_{z,A,S}}{\mathbf{r}_{x,A,S}} \right) \quad (6.9.2)$$

Lastly, one can calculate the progressive phase angles using (6.4.1) and (6.4.2). Equation (6.9.1) may return any angle up to 90° , but the maximum scan angle for θ is limited to about 30° , per the recommendation of [2].

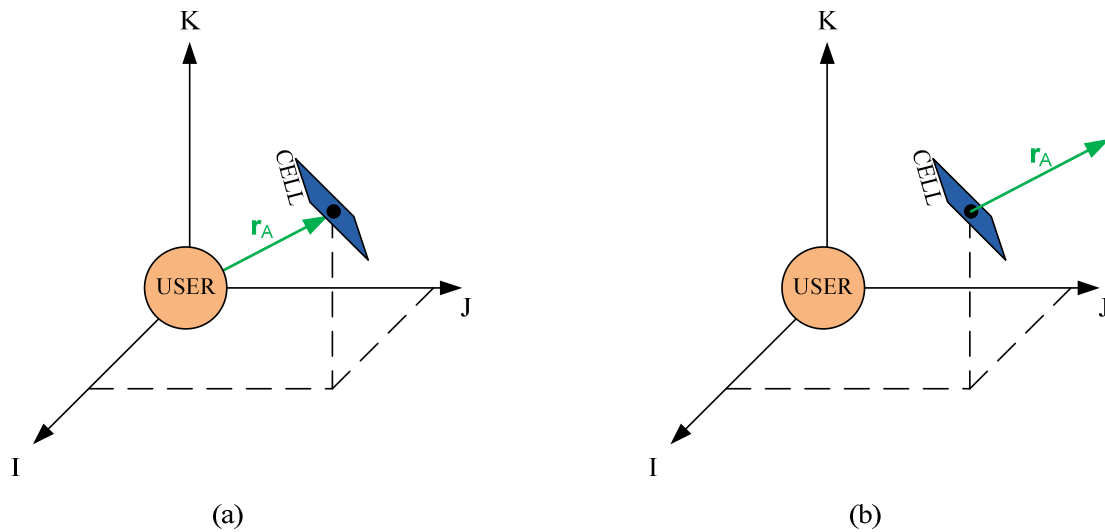


Figure 6.9.1 (a) Vector r_A , which points to the origin of frame S. (b) Affixing r_A to the origin of S provides the optimal direction for the main beam of the array.

6.10 ADDITION TO THE MODEL

The flow diagram that implements these calculations is shown in Fig. 6.10.1. The labels $\mathbf{p}_o$ and $\mathbf{p}_s$ represent vectors $\mathbf{r}_{A,O}$ and $\mathbf{r}_{A,S}$, respectively; and $\mathbf{F}$ is the currently simulated rotator matrix.

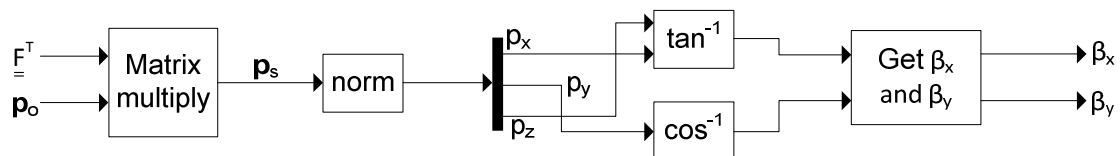


Figure 6.10.1 Flow diagram of the progressive phase shift calculations.

6.11 CONCLUSION / LOOKING AHEAD

With the beamforming array now controlled by the INS, a final performance analysis can be conducted. In chapter 7 the complete system will be simulated and radiation measured to see what kind of reduction in exposure users can expect when using a system of this type.

7 PERFORMANCE ASSESSMENT

7.1 INTRODUCTION

With the model complete, it is now possible to measure the effectiveness of the combined INS antenna array system. For this analysis, three typical motions a phone might experience are simulated and the percentage of radiation directed toward the user is measured. The three motions are: (1) a user turning his head, (2) a user rotating the phone in hand, and (3) the user picking up the phone. For comparison, assume a typical cellular phone's radiation pattern is omnidirectional, so that a high percentage of transmitted power is always directed at the user. The following simulations will be performed with both the uniform and binomial array excitations, but snapshots are shown only for the uniform field. Profiles of the radiation directed toward the user will be given for both the uniform and binomial array cases.

7.2 MOTION 1—TURNING THE HEAD

This motion simulates a user that turns the head, pauses, and turns back, all the time holding the phone to his/her ear. A few samples of this motion are shown in Fig. 8.6.1. In the figure, the small green sphere at the center is the user's head. The blue semi-transparent hemisphere shows the region of integration of bad radiation. The red lobes extending to the right and down in the snapshots are the radiation pattern of the uniform array.

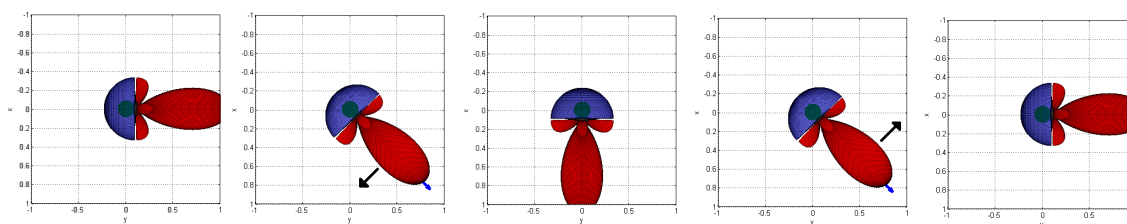


Figure 7.2.1 Snapshots of uniform array field as the user rotates his/her head.

As the user turns his head, the beam direction, though changing with respect to the user, does not change with respect to the phone. The direction normal to the surface of the phone always presents the optimal direction for the beam, which is why the beam shape is unchanging across all the frames. For this reason, the motion of the user turning his head is rather trivial. The INS plays no role, because the radio beam never needs to be moved from its nominal direction. This motion does demonstrate the effectiveness of the antenna array (no radiation is directed at the user), but not the INS.

7.3 MOTION 2—ROTATING THE PHONE

In this motion, the user rotates the phone in his/her hand; first about the x-axis, then about the y-axis, then about the z-axis. This motion is more complex from the beam directing perspective, and is a little easier to see if broken up into three sub-motions.

7.3.1 X-AXIS ROTATION

In the first part of the motion, the phone is rotated about the x-axis, as shown in Fig. 7.3.1.1. As the phone is rotated, a side lobe of the radiation pattern is seen to impinge on the user. In (b) and (c) of the figure, the back radiation from both the uniform and binomial arrays are shown. The binomial array exposes the user to about half the radiation as the uniform array. Both configurations are much better than a typical cellular antenna.

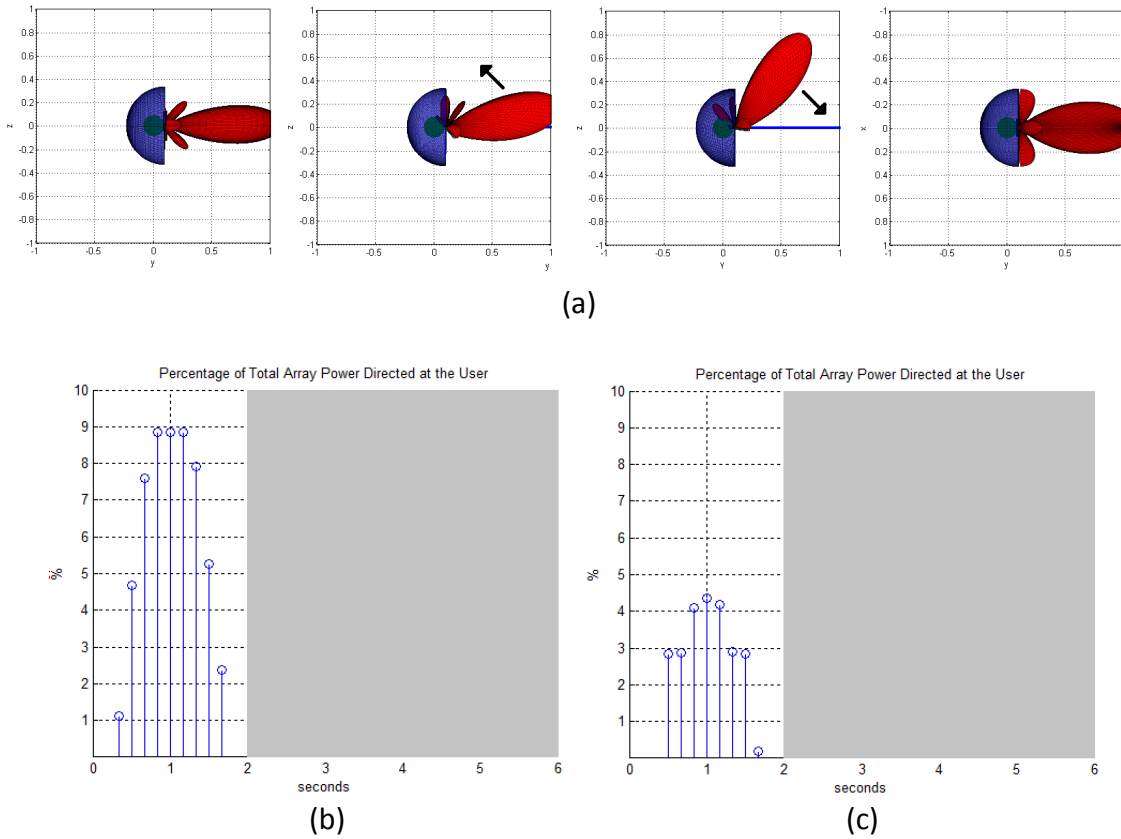


Figure 7.3.1.1 (a) In this yz-plane view, the phone is rotated about the z-axis. (b) Back radiation for the uniform array. (c) Back radiation for the binomial array.

7.3.2 Y-AXIS ROTATION

In the second part of the motion, the phone is rotated about the y-axis. This motion represents a trivial situation similar to section 7.2, in which the beam's natural direction is also the optimal one. In Fig. 7.3.2.1 no radiation reaches the user for rotations for either type of array.

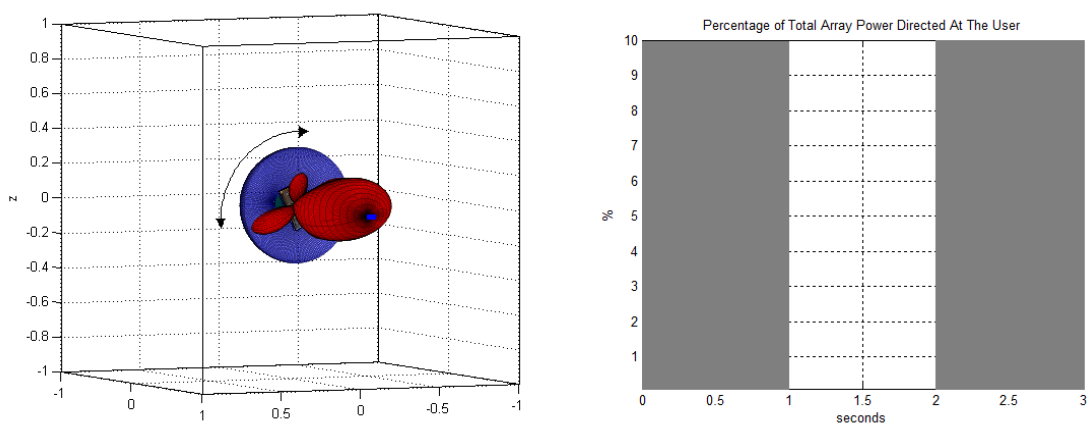


Figure 7.3.2.1 In this 3D view, the phone is rotated about the y-axis. No radiation reaches the user.

7.3.3 Z-AXIS ROTATION

In the third part of the motion, the phone is rotated about the z-axis, as shown in Fig. 7.3.3.1. As with the x-axis rotation of section 7.3.1, a side lobe of the radiation pattern is seen to impinge on the user. In (b) and (c) of the figure, the back radiation from both the uniform and binomial arrays are shown. Unlike in section 7.3.1, binomial excitation exposes the user to slightly more radiation than the uniform array.

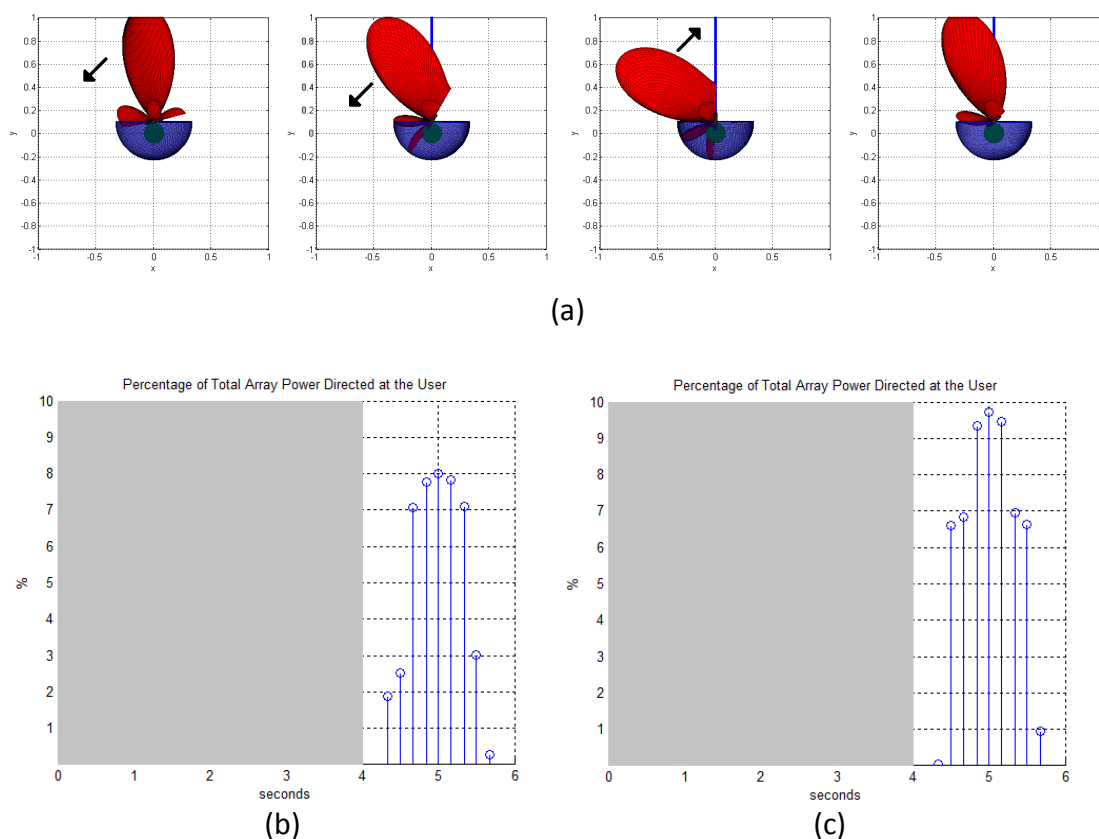


Figure 7.3.3.1 (a) In this xy-plane view, the phone is rotated about the x-axis. (b) Back radiation for the uniform array. (c) Back radiation for the binomial array.

7.4 MOTION 3—USER PICKS THE PHONE UP FROM TABLE

In this motion, the user picks up the phone from a table or desk and brings it to his ear. The phone is initially lying with antenna facing down and the top of the phone away from the user. Fig. 7.4.1 shows the snapshots and bad radiation percentage for this motion. Comparing the uniform and binomial arrays, the binomial array outperforms the uniform array, exposing the user to about half the radiation as the uniform array.

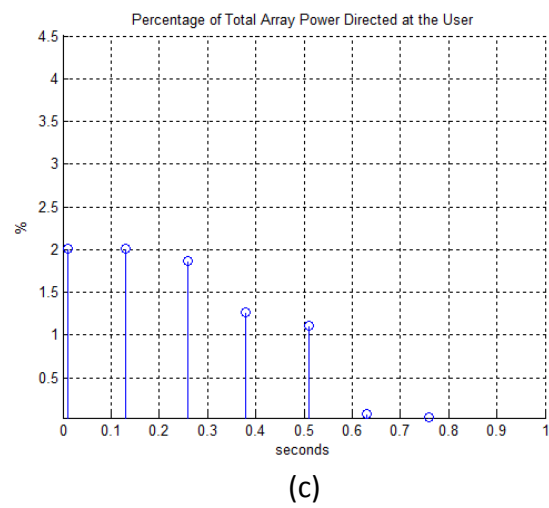
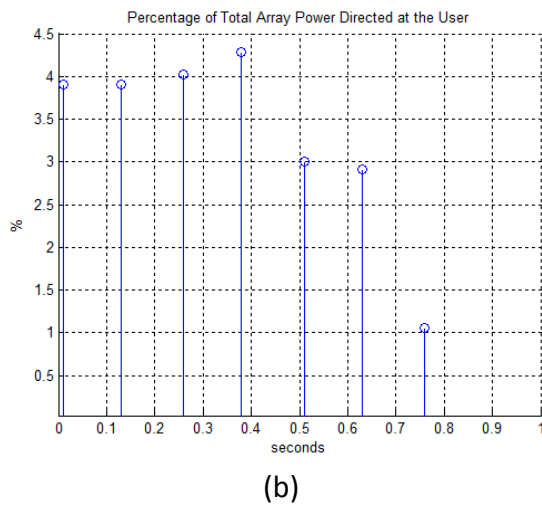
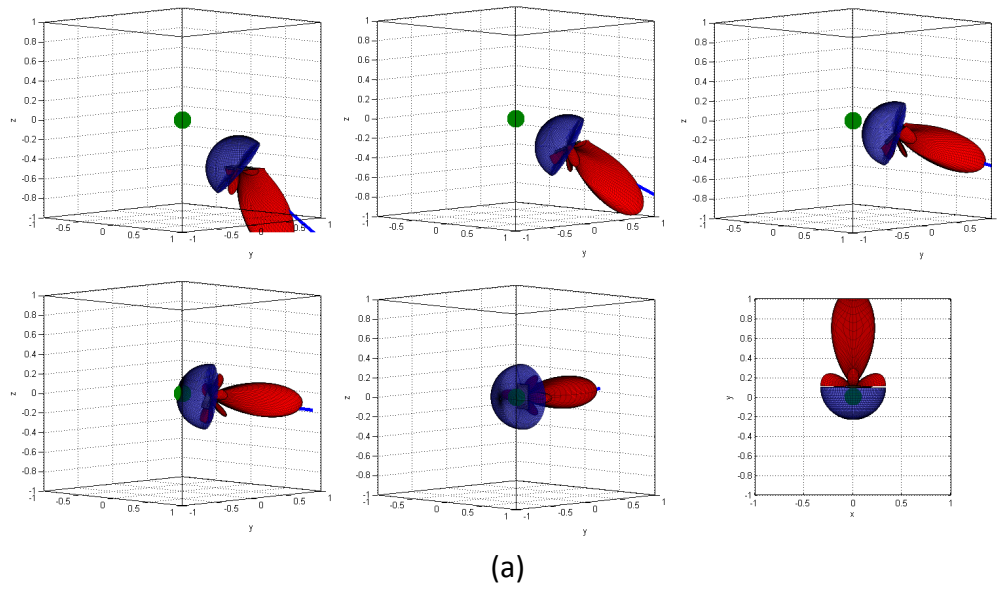


Figure 7.4.1 (a) User picks up the phone from a desk or table and brings it to his/her ear. (b) Back radiation for the uniform array. (c) Back radiation for the binomial array.

7.5 CONCLUDING REMARK

The total system performs well and the binomial array typically outperforms the uniform array. The only time the uniform array outperforms the binomial array is near the scan angles $\theta=90^\circ$, $\phi=\{0, \pi\}$. In these cases, the binomial array's beamwidth is greater than twice maximum scan angle, so a portion of the main beam impinges on the user. A zoomed in view for the binomial array is shown for this situation in Fig. 7.5.1.

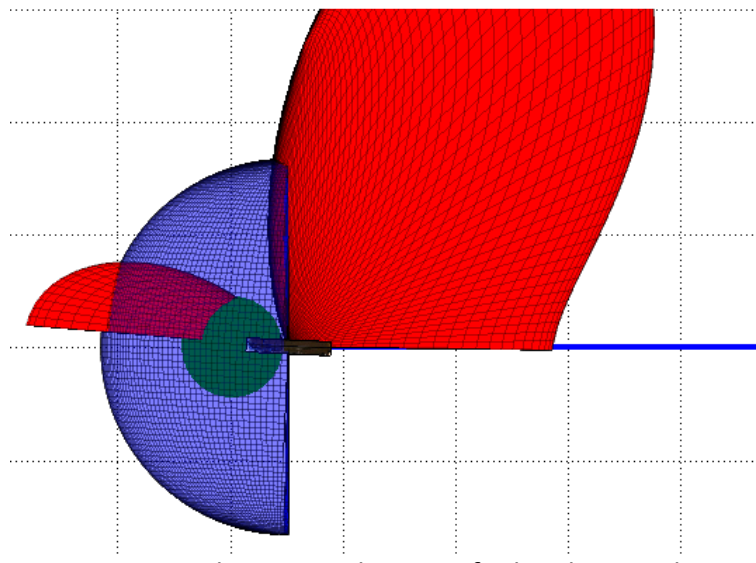


Figure 7.5.1 The main beam of the binomial array sometimes enters the plane of the user for extreme rotations of the phone. This does not happen for a uniform array (compare to snapshot 3, Fig. 7.3.3.1(a)).