GEOTEXTILE ANTENNA DESIGN FOR MOBILE PHONE COOPERATIVE COMMUNICATION RELAY NODE

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GEOTEXTILE ANTENNA DESIGN FOR MOBILE PHONE COOPERATIVE COMMUNICATION RELAY NODE

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GEOTEXTILE ANTENNA DESIGN FOR MOBILE PHONE COOPERATIVE COMMUNICATION RELAY NODE

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Houmin Li, son of Qipeng Li and Aidi Wang, was born in Beijing, China on December 5th, 1982. Upon graduating from Beijing No.4 High School in Beijing, Houmin chose to attend Tsinghua University where he received his Bachelor of Science degree in Materials Science and Engineering. Houmin achieved his Master of Science degree in Materials Science and Engineering in August of 2006, University of Southern California, Los Angeles, CA. Upon his graduation, Houmin moved to Auburn, AL where he enrolled into Auburn University's Graduate School and pursued a Master of Science Degree in Polymer and Fiber Engineering in the Department of Polymer and Fiber Engineering under the direction of Dr. Gwynedd Thomas. Luckily, Houmin met his lovely wife, Beibei Xu, daughter of Feng Xu and Shulan Gao, and had an adorable baby, Mark Li.

THESIS ABSTRACT

GEOTEXTILE ANTENNA DESIGN FOR MOBILE PHONE COOPERATIVE COMMUNICATION RELAY NODE

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The geotextile is widely applied in civil construction where textile materials can offer a distinct advantage. It can be electrified by weaving conductive strips into the textile structure. This could give the geotextile electromagnetic wave transmission capability and make the geotextile material into a geotextile antenna. The geotextile antenna is an ideal candidate for future wireless network relay systems.

In this research, the radiation mechanism of woven conductive structure is studied. Geotextile antenna prototypes are designed according to microstrip antenna theory and the prototypes are tested in an operating antenna range. The test result is compared with a computer aided antenna simulation result, and the radiation mechanism of the geotextile antenna is revealed. A logical discussion is given, and the result shows that the woven structure could disturb the lowest resonant mode of microstrip antenna, while the second lowest resonant mode of microstrip antenna remains. Moreover, the geotextile antennas possess a resonant mode even lower than the lowest resonant mode of microstrip antennas. This is explained by the textile nature giving the geotextile antenna a structure of a half wavelength dipole antenna array. As a result, the radiation mechanism of the designed geotextile antenna is a combination of a half wavelength dipole antenna array and the second lowest mode of a microstrip antenna. The discovered mechanism is useful for design optimization for the future, it is predicted that a low profile, multiband geotextile antenna can be fabricated according to this new theory.

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NOMENCLATURE

AMPS	Advanced mobile phone services
BER	Bit error rate
CDMA	Code division multiple access
DBS	Direct broadcasting system
DCS	Digital cellular system
DOA	Direction of arrival
ERP	Effective radiated power
FCC	Federal Communications Commission
FDD	Frequency division duplex
FDMA	Frequency division multiple access
GA	Geotextile antenna
GPS	Global positioning system
GSM	Global system for mobile communications
G/T	Gain-to-noise temperature ratio
IF	Intermediate frequency
LEOS	Low earth orbit satellite
LMS	Least mean square
LS	Least square
MIMO	Multiple-input multiple-output
MMIC	Monolithic microwave integrated circuit
MSA	Microstrip Antenna
NMT	Nordic Mobile Telephone
PDC	Personal digital cellular
PIFA	Planar-Inverted-F Antenna
QoS	Quality of service
RF	Radio frequency
RL	Return Loss
RMS	Root mean square
SDMA	Space division multiple access
SIR	Signal-to-interference ratio
SNR	Signal-to-noise ratio
TDMA	Time division multiple access
UHF	Ultrahigh frequency
UMTS	Universal Mobile Telecommunications Systems
VHF	Very high frequency
WCDMA	Wideband Code division multiple access

CHAPTER 1

INTRODUCTION

In 2007, the total number of mobile phone subscriptions in the world reached 3.3 billion. However, none of the mobile wireless company totally eliminated complaints about call blocking, dropped calls, access failures and outage of service. The quality of service (QoS) issues is the major concern of mobile customers when choosing wireless company [1]. Many wireless companies try to fulfill their customer need and compete with others by building more cellular base stations [2].

However, base stations are expensive. A brand new cell tower, industry terms, "Green Field Tower" normally costs between $75,000 and $230,000 to build with the average being around $120,000 [3]. According to cellular technology theory, the infrastructure of mobile phone communication is based on dividing the service area into overlapping cells. Each cell is served by an individual cell tower with power and control units. This configuration allows an efficient reuse of frequency thus greatly increased the efficiency of mobile phone communication within populated areas [4]. However, this theory also put a power usage limitation to the cell towers. In order to confine service range to geographical cells, the cell towers are operated at low power levels, typically around 35 watts, compared to millions of watts for TV broadcasting towers. As a result, each cell tower can cover only a very limited area and territorial factors may greatly affect its signal quality and cause “dead zones” in cities, mountainous and rural areas.

Due to the existence of these no-service areas, dropped calls, access failures and outage of service occur, which are major complains from mobile phone customers. Moreover, cell towers are fragile to environmental factors such as wind pressure, dust, rain, snow, severe weather and most challenging, lightening strike [5]. When damaged by weather, cell towers are out of service, putting the customer at emergency needs at risk. Overall, it could be very costly and impractical to build a nationwide cellular network with erected cell towers.

The future mobile network is going to be a low cost “5W” (Whoever, Wherever, Whenever, Whomever, Whatever) global communication system based on Cooperative Networking Theorem (CNT). According to this theorem, development of reliable relay nodes within an acceptable budget to connect mobile base station and mobile users is essential. Cell phone repeaters function as signal relays can improve mobile service coverage and QoS. However, it is designed to be for home use only and lack of the potential to be applied as communication infrastructure.

Geotextile, a material commonly used in roadbed construction, has the potential of embedding mobile communication antenna and relaying communication signals. Its advantage is having the potential to expand signal coverage to anyplace the roadbed covers. Accordingly, a geotextile antenna prototype for future CNT relay node is proposed. Despite of building more cell towers, which is very costly, an alternative mobile phone infrastructure extension method is suggested [6]. By periodically burying a series of antennas under roadbed, mobile phone network can be expanded along roads across the country. In previous work, antennas buried under ground are shown to be able to transmit signals through asphalt [6]. On the other hand, woven structure antennas have already been studied for wearable WLAN and GPS applications [4-7]. However, geotextile antenna design is a systematic project, and there are numerous factors to consider including the type of geotextile fiber, type of conductive fiber, type of substrate, method of fiber arrangement (weaving method), method of signal fabric/substrate arrangement, feed arrangement, environment properties (moisture, grounding, asphalt properties, soil properties, uneven surfaces) and so on [7]. A simple design mimic from wearable textile antenna will not meet the requirements for geotextile antennas. Only with careful planning and extensive testing, a proper antenna structure can be made to optimize the whole system performance. In reference [6], the actual woven geotextile antenna structure design remains untouched. This paper herein presents computer aided antenna designs and optimization, actual fabrication of the woven geotextile structure, and indoor testing result of the geotextile antenna system.

CHAPTER 2

BACKGROUND AND OBJECTIVES

2.1 Antenna Technology Basics

In this section, the basic concept of an antenna is presented and the working mechanism is explained. In addition, some important parameters of antenna design are discussed.

2.1.1 Introduction

An antenna is a conductive component designed to send and receive radio waves. It is a transitional structure between the circuit and the free space.

In order to know how an antenna radiates, how electromagnetic (EM) radiation occurs should be explained first. Radiation in a conductive wire is caused by time-varying current or an acceleration (or deceleration) of charge. If there is no acceleration (or deceleration) of charges in a wire, there is no energy radiated. That means if the charges are moving with uniform velocity along a straight wire, no radiation will occur, but, charges moving with uniform velocity along a curved or bent wire will radiate. If the charges are oscillating with time, radiation could occur even along a straight wire [8, 9].

2.1.2 Antenna Parameters

Input impedance

The input impedance of an antenna is the impedance presented by an antenna at its terminals or the ratio of the voltage to the current at the pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point [9]. Hence the impedance of the antenna can be written as:

$$Z_{in}=R_{in}+jX_{in} \qquad \text{Eq.2.1}$$

Where Z_{in} is the antenna impedance at the terminals

R_{in} is the antenna resistance at the terminals

X_{in} is the antenna reactance at the terminals

Voltage Standing Wave Ratio (VSWR)

Figure 1 shows an equivalent circuit of transmitting antenna. For an antenna to radiate efficiently, the power transferred from the transmitter to the antenna must be maximized. Maximum power transfer can only occur when the impedance of the antenna (Z_{in}) is matched to that of the transmitter (Z_S).

When such matching condition is not satisfied, some of the power will be reflected to the transmitter. This could cause standing waves, which can be characterized by the parameter Voltage Standing Wave Ratio (VSWR).

The VSWR can be expressed as [8]:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \qquad \text{Eq.2.2}$$

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_{in} - Z_S}{Z_{in} + Z_S} \qquad \text{Eq.2.3}$$

Where Γ is called the reflection coefficient

V_r is the amplitude of the reflected wave

V_i is the amplitude of the incident wave

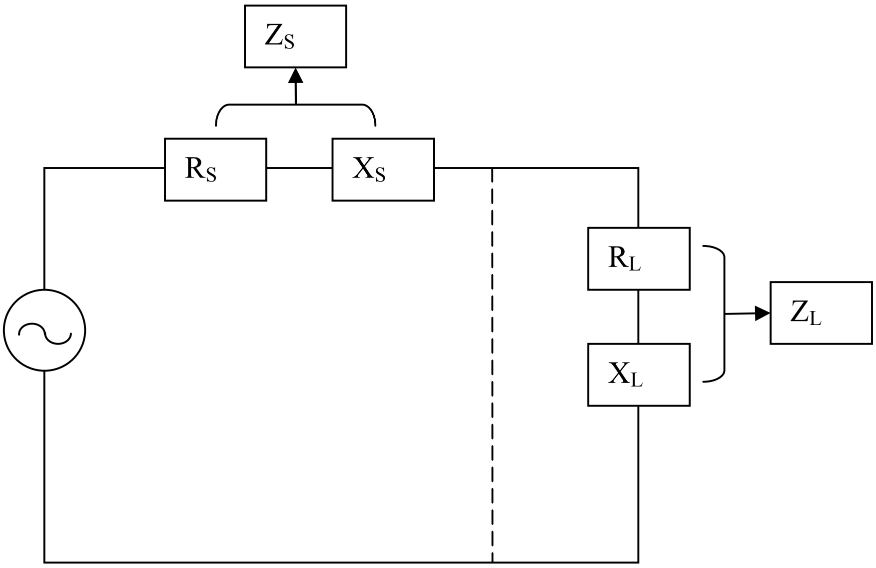


Figure 1. Equivalent Circuit of Transmitting Antenna

The VSWR represents the impedance mismatch between the transmitter and the antenna. The higher the VSWR, the greater the mismatch will be. The theoretical minimum VSWR which corresponds to a perfect match is unity. A practical antenna design should match an input impedance of 50Ω which is the impedance of the coaxial cable.

Return Loss

The Return Loss (RL) is a parameter similar to VSWR. It is a parameter indicating the amount of power that is lost to the load and does not return as a reflection. As explained in VSWR section, reflected waves lead to the formation of standing waves when the transmitter and antenna impedance do not match. So the RL is a parameter indicating how well the transmitter and antenna matches. RL can be expressed as [8]:

$$RL = -20\log_{10}|\Gamma| \text{ (dB)} \qquad \text{Eq.2.4}$$

When the transmitter and the antenna are perfectly matched, Γ=0 and RL=-∞ which means no power is reflected. On the other hand, when Γ=1, RL=0dB, which means all input power is reflected. For practical antenna applications, a VSWR of 2 is acceptable, this equivalent to a RL of -9.5dB.

Radiation Pattern

In the field of antenna design, radiation pattern refers to the directional (angular) dependence of radiation from the antenna [9]. The radiation pattern is directly related to the surface current and the radiation mechanism of the antenna. The radiation pattern is usually presented in polar form with a dB strength scale. Patterns are normalized to the maximum graph value, 0 dB, and directivity is given for the antenna. The plot is typically represented as a three-dimensional graph as shown in figure 2.

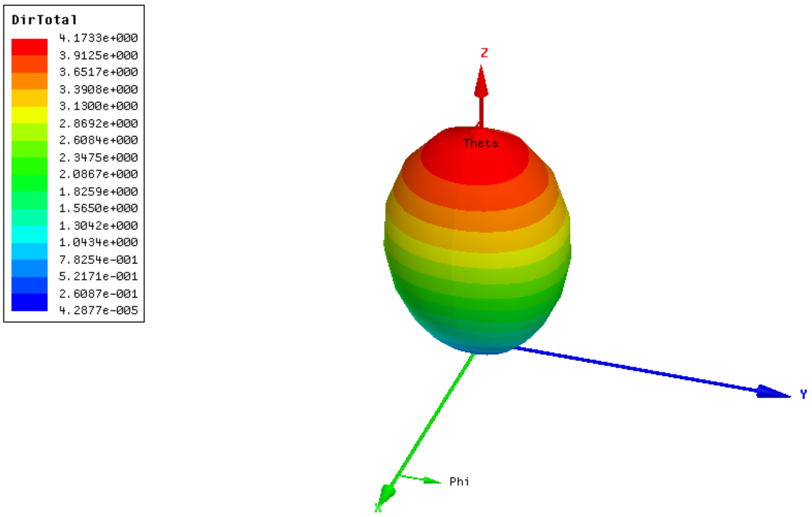


Figure 2. Radiation Pattern of Antenna

2.2 Mobile Communication Technology Overview

In this section, a brief overview of current mobile communication terminologies, principles, and future prospection is presented. Throughout the paper, “mobile” or “mobile phone” is used to denote the radio device on the move, including handheld or vehicle mounted.

2.2.1 Mobile Communication History

Mobile communication technology was first developed by AT&T Bell Laboratories during the 1960s and 1970s [10]. The researchers inverted the idea of conventional radio broadcast base station technologies of which higher altitude and greater power is preferred, to a controlled communication range with a limited power base station. Such an alternative opened the possibility for service area cellular regional division and frequency reuse [11]. In 1987 NTT launched the first commercial mobile phone service. During 20 years, mobile communication technology has developed from first generation AMPS or FDMA standards, to second generation TDMA or CDMA standards (including PCS, GSM, DCS 1800, IS-54, IS95) and finally commercial availability of third generation CDMA2000/WCDMA/TD-CDMA standards. This continuous development greatly increased the data rate and coverage of mobile communication and stimulated the expansion of mobile communication market. In 2007, the total number of mobile phone subscriptions in the world has reached 3.3 billion, which is half of the total human population. It also makes the mobile phone the most widely spread technology and the most common electronic device in the world [12].

2.2.2 Base Station

Mobile phones communicate with the communication network by means of radio link with base stations fitted with microwave antennas. Base stations antennas are usually mounted on towers, poles or buildings, located throughout populated areas. Base stations are connected to mobile communication switching center and then connect to the cabled communication network. A radio link between mobile phone and base station has two types of channels, they are control channels to transmit control signals and traffic channels to transmit messages [10].

Mobile phones communicate with base stations by low-power transceivers. The handheld modern mobile phone which is held inches from the user’s skull is limited to 0.6 watts ERP. This placed a limit to handheld mobile phone communication range and renders them less useful in rural areas where no base stations are nearby.

2.2.3 Multi-Access Schemes

The base station has to have the ability to reach multiple users in its service range. This is mainly achieved by three basic schemes: FDMA, TDMA and CDMA.

FDMA divides the whole service spectrum into separate carrier frequencies. Each user is assigned with two frequencies, one for uplink, and the other for downlink. FDMA is the very first scheme developed for mobile communication and it is mainly used with analog signals. Analog signal usually causes carrier frequency idling, thus FDMA efficiency is significant lower than later developed schemes.

TDMA scheme is applied with digital signals. It allocates different time slots to the subscribers using the same carrier frequency to realize frequency reuse. The control unit of TDMA controls the time slot assignment in an ordered manner so the reuse of carrier frequency is well organized. For detailed information of TDMA scheme please see references [13] and [14].

CDMA is a spread spectrum scheme which uses the whole carrier frequency bandwidth simultaneously while assigns a different codes to each user to reduce the spectrum density and increase the total capacity. Since CDMA signals occupy the same bandwidth, they appear as random noise to each other. Detailed CDMA information can be found in references [9-13].

2.2.4 Channel Assignment

The term "Channel" is traditionally used to denote a carrier frequency in the FDMA scheme. In mobile communication, it is also used to denote a time block for

TDMA scheme and a code in CDMA scheme or a combination of these three in a mixed system.

Channel assignment is a procedure controlled by the base station’s control unit. Because of the limited number of channels of each scheme, a fixed pool of channels is assigned to each the base station before it operates commercially. During operation, the base station communicates with each mobile user with three channels, one control channel and two message channels. These channels are from the channel pool of the specific the base station assignment at the planning stage.

There are two tactics of channel assignments for mobile user. One is fixed channel assignment. At the initiation of the call, the mobile user is assigned with fix channels to communicate with the base station until the call ends. The other tactic is dynamic channel assignment. This is a more efficient way compared to fixed channel assignment. Before channel assignment, the least interfering channels are found monitored periodically. The channel assignment during calls may change from a high interference one to a low interference, the so-called quiet channel [10, 15, 16]. This tactic ensures the system operating at a low interference level.

2.2.5 Channel Reuse

As mentioned, the total number of channels is limited in any of the mobile communication schemes. As a result, the system capacity is limited for carrying simultaneous calls. For conventional broadcast type radio communication system, the only way to increase the capacity is to improve coding technology and make the channel usage more efficient, even though the possible improvement is very limited. However, for mobile communication, the other way to accomplish this is by using the same channel again and again. This is achieved by using the same channel far away from each other that they won't interfere with each other. A minimum distance between two cells using identical channels is required and is known as the channel reuse distance. The capacity of mobile communication system is then determined by the channel reuse distance [10].

The concept of the channel reuse is shown in Figure 3 [11]. The service area is divided into hexagonal shaped cells with 7 different frequencies assigned to different cell. The cells with same frequency are place far away from each other to eliminate co-channel interference. Shift parameters i and j are defined as the steps of cell movement along the two axes of hexagons to reach the nearest co-channel cell. Configuration in Figure 3 shows i = 4 j = 3. The number of cells in a cluster can be calculated by

$$N = i^2 + ij + j^2 \qquad \text{Eq.2.5}$$

And the frequency reuse distance is given by

$$D = R\sqrt{3N} \qquad \text{Eq.2.6}$$

R is the radius of the cell.

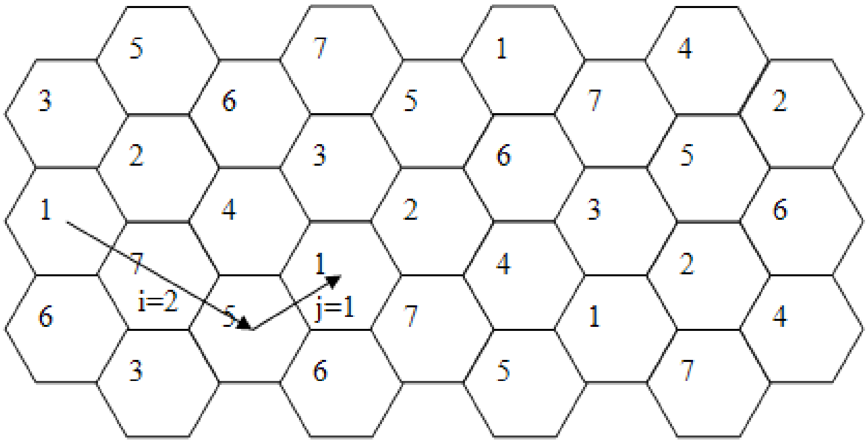


Figure 3. Channel Reuse Concept of Cellular Technology.

The ratio of D over R is called the co-channel reuse ratio as shown in Table 1. Choice of co-channel reuse ratio is determined by co-channel interference considerations. As the co-channel reuse ratio increases, the distance between co-channel cells increases, thus reduces the probability of poor signal-to-interference condition. For more discussion on how to choose proper frequency reuse ratio please see [11].

Table 1. Frequency Reuse Ratio and Number of Cells in a Cluster

N	[i, j]	reuse ratio
4.00	[2, 0]	3.46
7.00	[2, 1]	4.58
12.00	[2, 2]	6.00

2.2.6 Mobile Radio and Cellular System

Conventional radio stations usually use the highest possible antennas and maximum power to reach users as far as possible. In such a system, communication capacity is limited by the number of channels of the communication band. With crowded frequency usage of today’s radio frequency spectrum, it is impossible that such a system could support simultaneous communication for a mid-sized city. Cellular systems, on the other hand, introduced a channel reuse strategy to support vast number of simultaneous communication. In a cellular system, the service area is divided into small cells. Each cell is served with its own the base station and a set of frequency. Cells far away enough from each other can reuse the same frequency without co-channel interference as described previously.

When a base station has reached its capacity limit, cell splitting or cell sectorization can be applied. Cell splitting is the process of splitting a mobile cell into several smaller cells. This is usually done to make more voice channels available to accommodate traffic growth in the area covered by the original cell, as shown in Figure 4. Each new cell has its own base station and sub-service-cell. The power of new base stations is adjusted, normally lowered to fit the newly assigned service boundary. The consequence of cell splitting is that all the frequency has to be reassigned in order not to affect the neighboring cells. Cell sectorization, on the hand, is to subdivide the current cell into sectors, with all the sectors served by the original base station, as shown in Figure 5. This can be achieved by employing directional antennas so that different sectors are served by different antennas.

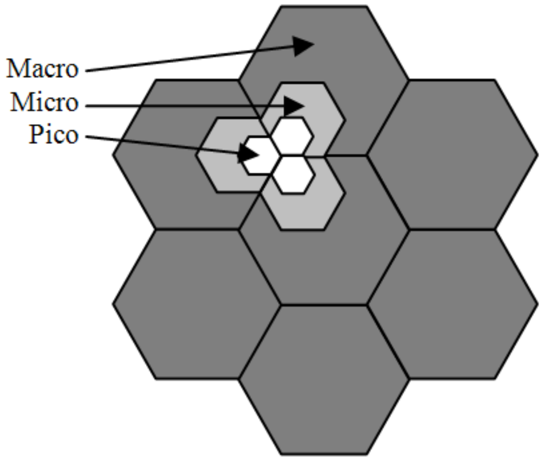
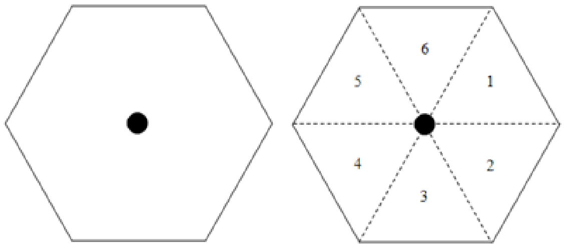


Figure 4. Cell splitting



Omni-direction
Sectorized

Figure 5. Cell sectorization

2.2.7 Dipole Antenna Array

For some applications single element antennas are unable to meet the antenna requirements such as gain or radiation pattern. Arranging a series of single antenna elements in an array is a possible solution [17].

A dipole antenna array is an array formed by a series of single dipole elements. The dipole elements can be arranged to form a 1 or 2 dimensional array. We are focusing on the 1 D array in this research. The radiation pattern of the array changes with the way the antenna elements combine. An array factor is introduced to describe the behavior of arraying.[17]

$$AF = \frac{\sin(\frac{N}{2}\varphi)}{\sin(\frac{\varphi}{2})} \qquad \text{Eq.2.7}$$

Where $\varphi = kd\cos\theta + b$, N is the number of elements making the array, k is the wave number and $k = \frac{2\pi}{\lambda}$, λ is the wavelength. θ is the polar angle and b is the difference of phase between any two successive elements forming the array.

The array directivity increases with N. The spacing between elements also has an influence on the array factor. Larger element spacing results in a higher directivity as well. The element spacing is normally smaller than 1/2λ to avoid the occurrence of grating lobes. Grating lobes are unwanted peak value in the radiation pattern of the array.

The dipole array can be designed to radiate in either broadside (perpendicular to the array plane) or end fire (the same direction as the array orientation) such as shown in figure 6.

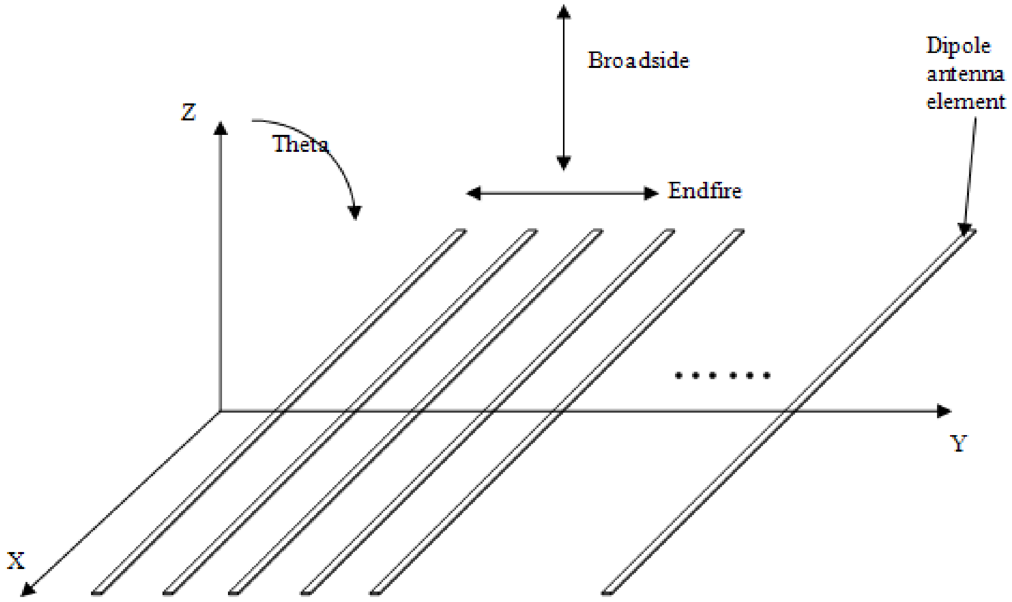


Figure 6. Topology of Dipole Antenna Array

Arraying of antennas makes diversity combining a possibility, which is an important technology used for combating fading channels [10].

2.2.8 Diversity Combining

Signal interference and fading are two of the major concerns in mobile communication. Diversity combining is a technology developed to combine multiple received signals into a single improved signal. This technology helps to overcome the problem of fading in mobile communication and technically requires the deployment of antenna arrays. The element of the antenna array is normally placed a few wavelengths apart and the received signal can be processed in various types of combining techniques.

The major difference between diversity combining and antenna array processing or beam forming is that diversity combining combines signal at the baseband. It does not affect the individual antenna pattern while increasing the signal level. It is very effective in reducing signal fading effect while antenna array processing and beam forming work better on reduce signal interference [11, 18].

2.3 Cooperative Communication and Relay Nodes

In this section, theories on how to utilize relay nodes and terminals themselves as part of cooperative diversity network are introduced. Compared with base station, signal fading of mobile network terminal is the most important concern. Cooperative communication theory is a promising solution to signal fading in mobile communication. Herein, a brief introduction of cooperative communication is present as well as a perspective of how the wireless network might look like in the future.

2.3.1 Cooperative Diversity of Wireless Networking

To improve Signal to Noise Ratio (SNR) and QoS of wireless base stations, diversity combining and antenna arrays has been incorporated in base station as a standard. However, unlike a base station which has unlimited space for antenna arrays, handset application is size-constrained, and an antenna array is not an option. To take advantage of diversity combining for handset applications, an alternative scenario, cooperative communication, has been suggested. The basic idea is that single antenna users can share their antennas to form a virtual MIMO system, with terminals helping each other transmit signals and with the help of relay nodes, improved data rate, coverage, SNR and QoS can be achieved [19].

It is estimated that future wireless network will have the capacity to communicate with any user, at anytime, anywhere on earth, at a high data rate. To achieve such a system, cooperative wireless network is the optimum solution. In a cooperative communication system, each wireless user not only acts as a terminal, but also acts as a cooperative agent for other users. With the help of optimized routing relay nodes, base stations and communication satellites, a global cooperative wireless network will be present [10, 19-23].

2.3.2 Wireless Network Relay Node

The wireless communication relay node is a critical component for the future wireless network. By definition, a relay node is a device that has good communication links with the base station and acts to help communication with other terminals that do not have [24]. With the help of repeaters, CDMA system has shown a two-fold increase of system capacity, and a 10% increase in coverage [21]. Since the SNR degradation due to repeater noise is insignificant compared with propagation loss [21], extension of cellular network into the non-coverage rural area could further increase the whole network coverage with only a fraction of the cost of new base stations.

Different relaying schemes have been studied in depth, including:

Facilitation: in which the relay does not actively help the source, but tries not to interfere with the source as much as possible.

Observation: in which the relay encodes a quantized version of the signal received with the idea of source coding with side information.

Cooperation: in which the relay completely decodes the received signal, re-encode and transmit to eliminate propagation noise [20].

According to cooperative communication theory, relay node is the critical component in cooperative communication network. Although relaying in communication network could cost an additional channel, the advantage gained through cooperative communication could result in dramatically increased coverage and data rate [21]. For different relaying schemes, outage probability for cooperation scheme decays proportional to $1/SNR^2$ compared to 1/SNR for schemes without cooperation. At fixed low data rates, the power usage of cooperation scheme is at 1.5 dB from optimal and offer large energy savings over direct transmission [20].

2.4 Microstrip Antenna

A microstrip antenna (MSA) is a low profile antenna. It is also named as patch or planar antenna. A MSA is a popular built-in antenna for electronics because of its lightweight, inexpensive, and conformal structures [25]. We are going to introduce a basic MSA, which is a rectangular flat plate over a substrate with a ground plane and a probe feed in the center. The structure of the MSA and its electric field distribution excited in its fundamental mode is shown in figure 7 [9].

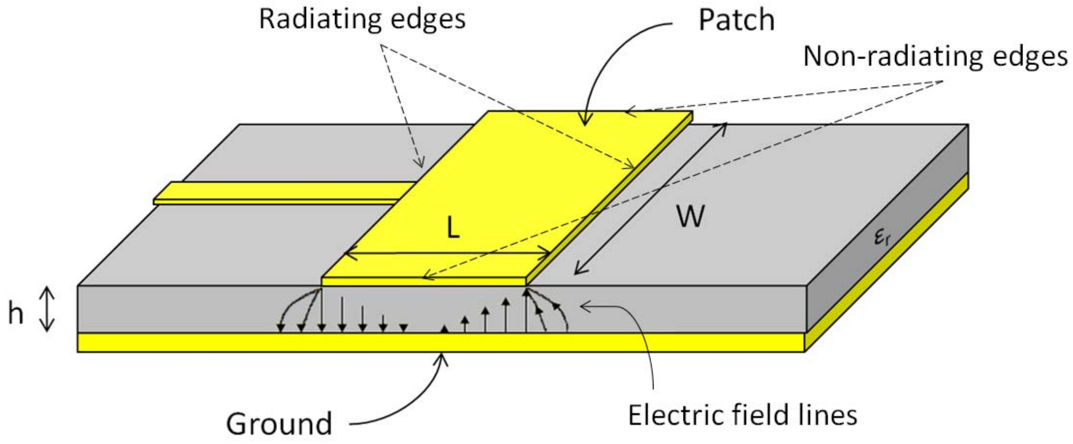


Figure 7. Microstrip Antenna Structure and Electric Field Lines

As the figure shows, the electric field of the MSA is zero at the center, maximum (positive) at one side, and minimum (negative) on the opposite side. When a signal is applied, the minimum and maximum continuously change sides according to the instantaneous phase of the signal [25]. The length L of MSA is the factor that causes resonance at its half-wavelength frequency. The radiating edges are the two edges at the ends of the L-dimension of the patch. Radiation that occurs at the ends of the W-dimension is far less compared to those at L-dimension edges, and is normally ignored.

There are several keys to successfully design a MSA structure. First, the structure needs to be a half-wavelength length resonator. Second, a low dielectric constant substrate for the MSA is preferred. Third, a thicker dielectric substrate could broaden the bandwidth, but the substrate thickness should always be just a fraction of a wavelength [26].

The resonant frequency of MSA is inversely proportional to its size. Because of this, MSA are mostly used for frequencies of microwave and above. For frequencies lower than microwave, MSA application is very limited because of the sizes required. For example, an MSA to receive FM radio at 100 MHz would be having the size on the order of 1 meter long, which is a very large circuit for any type of substrate. To receive AM radio at 1000 KHz, the MSA would have the size of a football field. [9] One application example of MSA is in satellite radio receivers (XM and Sirius) [26].

The radiation efficiency is determined by the patch width W and the impedance matching network. In order to achieve best radiation efficiency, W can be calculated according to equation 2.8 [9]

$$W = \frac{v_0}{2f_0}\sqrt{\frac{2}{\varepsilon_r + 1}} \qquad \text{Eq.2.8}$$

Where v_0 is the wave speed, f_0 is the resonant frequency, and ε_r is the dielectric constant.

The bandwidth of the MSA in general is proportional to its volume. For a rectangular MSA at a constant resonant frequency, it is determined by substrate thickness and dielectric constant [9]

$$BW \sim \frac{h}{\sqrt{\varepsilon_r}} \qquad \text{Eq.2.9}$$

A detailed MSA design procedure is presented in Chapter 3.

2.5 Planar Inverted-F Antenna

Modern mobile phone antenna requires compact size, light weight, conformity built in, omni-directional, multi-band operation and low fabrication cost. Conventional antennas such as helical and monopole antennas do not meet such requirements. PIFA with the property of operating at multi-band, and can be incorporated into mobile phone chassis with no extending parts, is the ideal choice for mobile phone handset antenna. PIFA has been studied intensively in the past 30 years.

PIFA is a combination of MSA and Wired Inverted-F Antenna. It begins with the idea of loading the antenna with high dielectric layer. MSA is a type of low profile antenna with a high dielectric constant substrate. This configuration can make the resonant size of the antenna smaller. But for mobile phone application which operates at 800MHz (AMPS), the resonant size of MSA $\lambda/2$ is equal to 187mm, which is still too large. In order to further reduce the size of MSA, researchers introduced Inverted-F structure into the antenna. A PIFA can be made as small as $\lambda/8$, for 800MHz, it means the resonant size antenna can be as small as 46.8mm.

A PIFA normally consists of a rectangular planar element, a finite ground plane, and a short-circuit plate of narrower width than that of a shortened side of a planar element [27]. On the other hand, the PIFA structure is considered as a linear inverted-F antenna with the wire replaced by a planar element to increase its bandwidth. The PIFA structure is considered as a short circuit MSA. By shorting the radiator element and ground plane at proper position, the size of radiator can be halved. The final structure can be described as a transmission line antenna with a wire element and a short-circuit MSA. Figure 8 shows the structure of Inverted-L, Inverted-F, and PIFA. Modification of PIFA is also applied to further lower its size. Techniques including meandered structure by cutting several narrow slits in the patch, which can increase the electrical length of the radiator element [28]. A generic PIFA applied in mobile phone nowadays is shown in figure 9 [29].

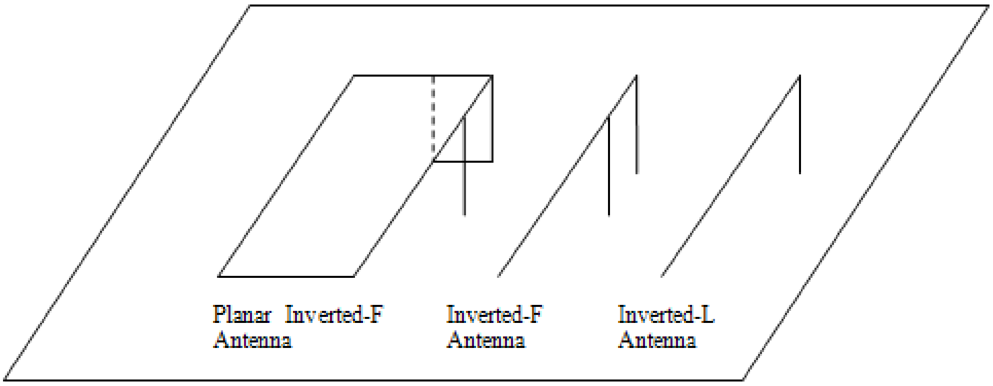


Figure 8. Planar Inverted-F Antenna

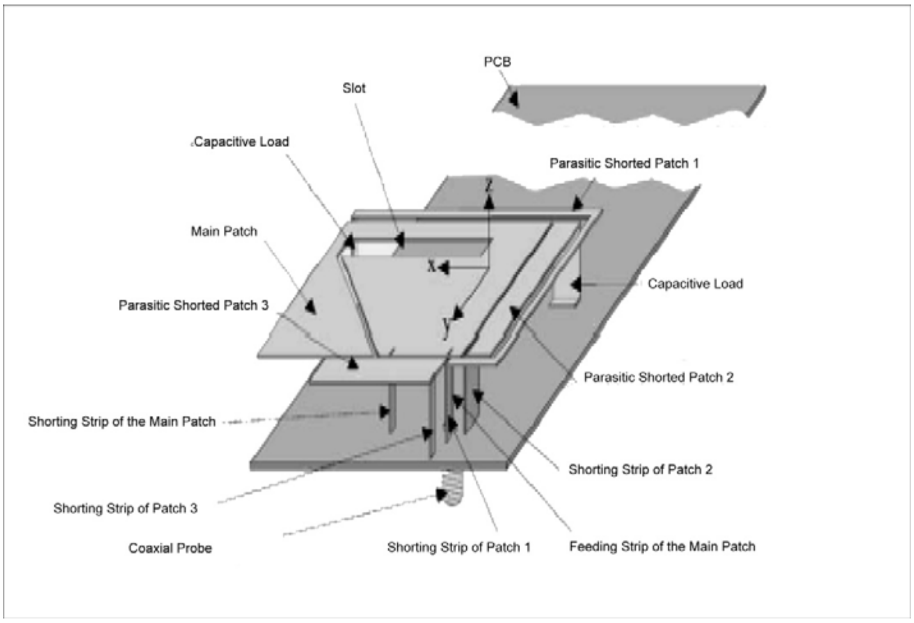


Figure 9. General Structure of Multi-band PIFA

2.6 Geotextile Antenna and Future Applications

Geotextile is a subcategory of textile material mostly used in civil engineering projects. It is usually applied in construction such as pavements, railroad beds, retaining wall earth embankment, rip-rap, concrete revetment and drain construction across the U.S. [30]. Geotextile can be electrified by incorporating conductive yarns in its woven structure. Electrified geotextile can be used to transmit and receive signals just like E-textile antennas [31]

Electronic textile or E-textile is a kind of fabric with electronic conductivity and electronic devices mounting capacity. E-textile combines the flexibility of traditional textile and the interconnectivity of circuit board. Its application including platform for wearable computer, personal medical monitor, space experiments, wearable mobile information infrastructure and low cost large scale applications. E-textiles opened up a new interdisciplinary field of research that recalls the cooperation of specialists from micro system, materials and textiles. The goal of this new area is to develop flexible, conformable and large-area textile based information system which has unique application in both civilian and military sectors [32].

Due to the miniaturization of wireless communication electronics, cellular phone handsets are the most abundant electronic device in the world. As cellular phone handsets getting smaller and smaller, its size limits the use of large-aperture antennas. Although smaller antennas can fit in these devices, the limited antenna aperture causes inferior antenna performance and lower radiation efficiency. E-textile antennas are promising solution. The next logical development of handsets is to incorporate wearable antenna to free user's hands. Many researchers have been studying E-textiles for wearable antenna applications including E-textile patch antenna for WLAN application [33], GPS application [34], mobile communication [35], dual band [36] and distributed antenna system [37].

Electrified geotextile can serve as antenna just like regular E-textile. Conventional antennas send/receive signals in the open air, while geotextile antennas can send/receive signal under asphalt [6], and the signal loss by transmitting through asphalt is minimal. Compared to conventional antennas which are normally erected towers facing weather damages including wind pressure, rain/snow corrosion and severe weather such as tornado and thunder attacks, geotextile antennas are built to work under the roadbed and are less sensitive to weather damages. By proper designing, geotextile antenna is a promising candidate for relay node antenna of future wireless communication network.

On the other hand, geotextile antenna has the potential of being used in airport runways as RF runway indicator for landing assistance system. The landing assistance system nowadays highly depends on the aid of GPS satellites and ground guidance station [38]. However, this scheme of landing assistance could not visualize the runway for the pilot under low visibility conditions [39]. Due to Doppler shift and the distance of signal from GPS satellites, the GPS system accuracy is limited. Moreover, the signal from ground station may be blocked by obstructions [39]. All of these increase the risk of current landing assistance system.

The best solution for landing assistance under low visibility conditions is to let the pilot virtually see the runway. Geotextile antennas placed under runway can serve this purpose. By incorporating omni-directional geotextile antenna arrays with the runway, the geotextile antenna can be fed with intensive pulse signals and work just like the high-intensity lighting arrays used in Instrument Landing System. While the signals are picked up by an incoming aircraft, a virtual image can be generated for the pilot to virtually see the runway under low visibility conditions. This can make the landing under low visibility condition as easy as under clear condition.

2.7 Objectives

The general objective of this research is to design a low profile, low cost geotextile antenna prototype that does not disrupt the woven structure and production technique of a geotextile. The prototype antenna is design to operate at the PCS cellular wireless system frequencies. Meanwhile, research is going to reveal the radiation mechanism of this geotextile antenna design and the effect of woven conductive structure on antenna performance. During the design process, understanding of the benefits, drawbacks and limitations of geotextile antenna are studied. As a result, this research is going to serve as a guideline for other woven structure antenna designs in the future.

CHAPTER 3

GEOTEXTILE ANTENNA DESIGN

3.1 Material Selection

Typical geotextile structures are composed of polypropylene (PP), PP and polyethylene (PE) blends, and polyester. Geotextile fabrics come in three basic forms: woven (like mail bag sacking), needle punched (like felt), or heat bonded (like ironed felt). The geotextile we discuss in this research is the woven type.

3.1.1 Geotextile Material

The roadbed geotextile used in this experiment is provided by Belton Industries, a specialty weaver with its major strength in polypropylene geotextile. The material is American Assoc. of State Highway & Transportation Officials (AASHTO) standardized Class 1 Stabilization. The finished fabric has a fabric weight of 220 g/m^2 (6.5 oz/yd^2). The geotextile yarn used in this design is a 22 picks/inch of 1000 denier polypropylene monofilament yarn. This yarn has a dimension of 2.03mm×0.102mm (0.08in×0.004in).

3.1.2 Conductive Yarn

The skin depth of copper yarn can be calculated by

$$\delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad \text{Eq.3.1}$$

Where ω is the frequency [radians/second], μ is the permeability of the material, dielectric constant [H/cm] and σ is the conductivity [Siemens/meter]. For copper material application at 1GHz, skin depth is 2.1μm. In order to guarantee the surface current density for maximized radiation, the tapes used in this antenna design must have a thickness greater than twice of the skin depth, which is 4.2μm.

The selection of conductive yarn in based on the dimension matching of geotextile yarns for better production adaptability. Copper is selected for base material for its good conductivity and relatively cheap price. The chosen yarn is from Ulbrich Industries, and it is originally used for solar cell interconnect flat wire (PV ribbon wire). The yarns have soldering material 62SN/36PB/2AG coating with thickness of 0.001-0.0015mm (400-600 micro-inches) per side as received, which make it easier to install the antenna feed structure. The conductive yarn must also meet other requirements. The dimension of the conductive yarn is 1.998mm×0.0991mm (0.0787in×0.0039in).

3.1.3 Substrate Material

The substrate used in this design is Rogers RT5880 high frequency laminate. It has a relative dielectric constant (ε_r) of 2.2 and a thickness (h) of 1.72mm.

3.2 Instrument

3.2.1 Ansoft HFSS

The Ansoft HFSS is a commercial finite element method solver for electromagnetic structures from Ansoft Corporation. The acronym originally stood for high frequency structural simulator. It is one of the most popular and powerful applications used for antenna design.

The antenna designs are going to be loaded into the software for simulation before put in test range to save time and budget. The software can also help optimizing the antenna design for certain performance parameters. The interface of the software is shown in figure 10 [40].

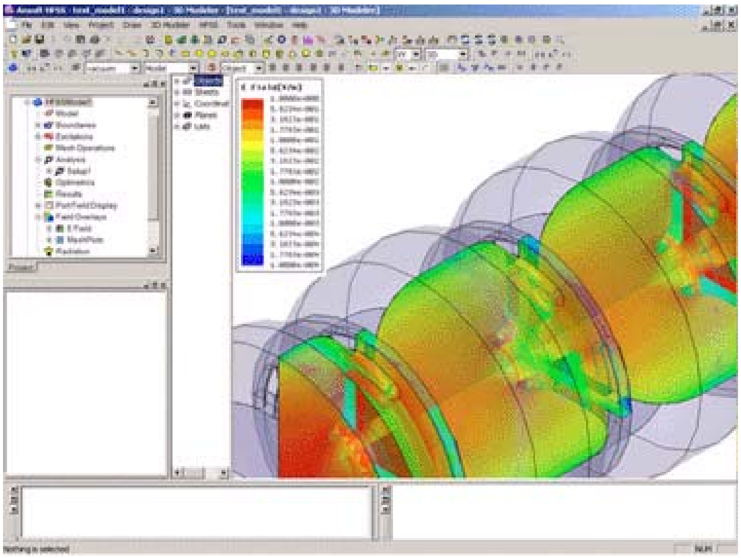


Figure 10. Ansoft HFSS

3.2.2 HP8753

The network analyzer used in this research is HP8753C as shown in figure 11. It is used to test antenna impedance match, resonant frequency, and SWR. The HP8753C is a High Performance RF Vector Network Analyzer. It has frequency coverage of 300 KHz to 3 GHz, optionally up to 6 GHz. It has a swept synthesized RF source and a sensitive receiver to ensure accurate results. The 8753C provides magnitude and phase information, offers 100dB dynamic range, makes group delay and time domain measurements and utilizes vector accuracy enhancement to minimize measurement uncertainty. A plotter is connected to the HP8753 to output the data collected. The plot is scanned into computer with a Lexmark scanner.

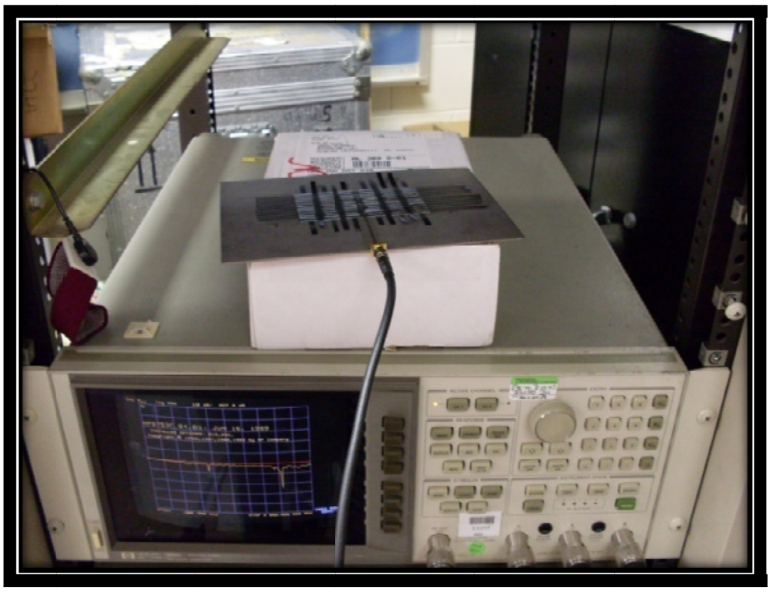


Figure 11. HP9753C Network Analyzer

3.3 Geotextile Antenna Design

The overall design process is shown in figure 12.

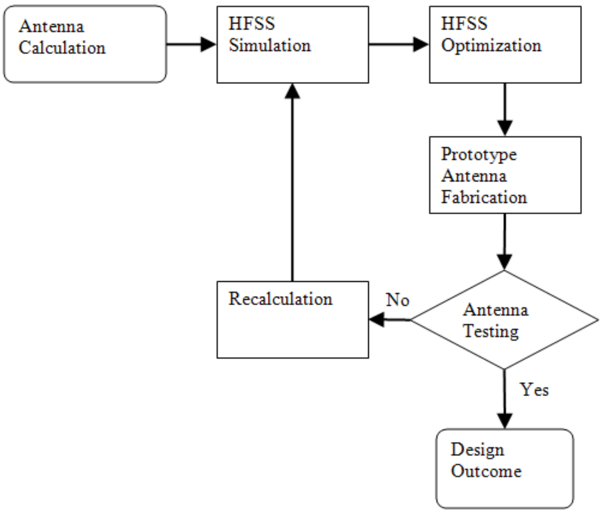


Figure 12. Flow Chart of Antenna Design Process

The resonant frequency of geotextile antenna is set based on the general cellular frequency shown in table 2. A low profile antenna serves broadband PCS is set as the goal of design. This is normally achieved through a Planar-Inverted-F (PIF) structure. However, geotextile structure is limited by weaving process. It is not feasible to create a PIF structure with weaving process alone. As a result, we decided to start the design from the basic MSA theory. A MSA antenna is also fabricated to serve as a reference antenna.

Table 2. General Cellular Frequency Table

American Cellular		
AMPS, N-AMPS, D-AMPS (IS-136) CDMA	824-849 MHz 869-894 MHz	uplink downlink
American PCS		
Narrowband	901-941 MHz	
Broadband	1850-1910MHz 1930-1990 MHz	uplink downlink

3.3.1 Design of Reference MSA

The MSA design follows the microstrip transmission line theory. This theory simplifies the MSA into two slots of width W, height h, and separated by a transmission line of length L as shown in figure 13. The microstrip is an interface of two types of dielectrics, typically the substrate and air.

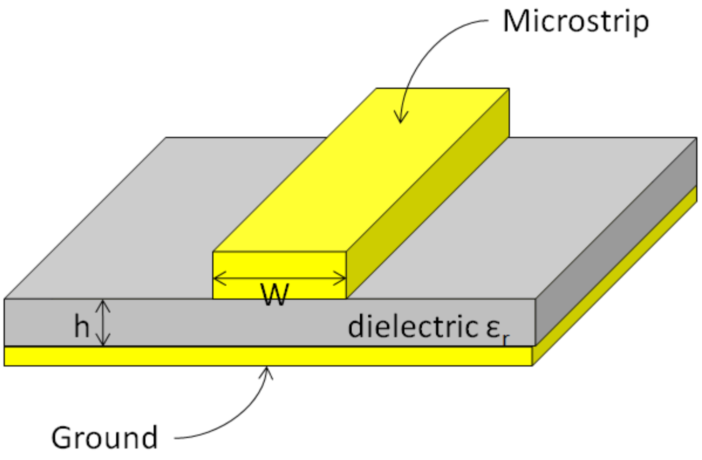


Figure 13. Microstrip Transmission Line

The design of reference MSA followed the steps from Balanis [9]:

1. Calculate the practical width that leads to good radiation efficiencies

2. Determine the effective dielectric constant of the MSA
3. Determine the extension of the length ΔL
4. Calculate the effective length

Specification of antenna design:

Frequency of operation (f_0): this is the resonant frequency of the antenna. The resonant frequency must be selected to match the commercial cell phone frequency in order to relay cell phone signal. 1850.0–1910.0MHz (uplink) 1930.0–1990.0MHz (downlink) bands are the frequency range assigned to broadband Personal Communication System (PCS-1900). So the target frequency of our antenna design is set to 1900MHz.

Dielectric constant of the substrate (ε_r): The dielectric constant of Rogers RT5880 is 2.2.

Height of dielectric substrate (h): the substrate has a height of 1.72mm.

Utilizing the transmission line model,

Step 1: Calculation of microstrip Width (W): the width of the MSA is given by

$$W = \frac{c}{2 f_0 \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \qquad \text{Eq.3.2}$$

Where c is the speed of light, ε_r and f_0 are previously defined.

Substituting $c=3\times10^8$m/s, $\varepsilon_r=2.2$ and $f_0=1.9$GHz, we get:

W=59.29mm

Step 2: Calculation of effective dielectric constant (ε_{reff}):

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}[1 + 12 \times \frac{h}{W}]^{-\frac{1}{2}} \qquad \text{Eq.3.3}$$

Substituting ε_r=2.2, W=59.29mm and h=1.72mm, we get:

ε_{reff}=2.117

Step 3: Calculation of effective length (L_{eff}):

$$L_{eff} = \frac{c}{2 f_0 \sqrt{\varepsilon_{reff}}} \qquad \text{Eq.3.4}$$

Substituting ε_{reff}=2.117, c=3×10^8m/s and f_0=1.9GHz, we get:

L_{eff}=52.26mm

Step 4: Calculation of length extension (ΔL):

$$\Delta L = 0.412h \times \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \qquad \text{Eq.3.5}$$

Substituting ε_{reff}=2.117, W=59.29mm and h=1.72mm, we get:

ΔL=2.255mm

Step 5: Calculation of actual microstrip length (L):

$$L = L_{eff} - 2 \times \Delta L \qquad \text{Eq.3.6}$$

Substituting L_{eff}=52.26mm and ΔL=2.255mm, we get:

L=49.75mm

Step 6: Calculation of edge impedance (Z_L)

The edge impedance given by [9]

$$Z_L = 90 \times (\frac{{\varepsilon_r}^2}{\varepsilon_r - 1}) \times (\frac{L}{W})^2 \qquad \text{Eq.3.7}$$

Substituting W=59.29mm, h=1.72mm, and ε_{reff}=2.117 we get:

Z_L=254.25Ω

Step 7: Impedance matching:

The impedance matching is realized by a λ/4 transformer. The impedance of the transformer (Z_T) is given by:

$$Z_T = \sqrt{Z_L \times Z_S} \qquad \text{Eq.3.8}$$

Substituting Z_L=254.25Ω, Z_S=50Ω we get:

Z_T=112.74Ω

Quarter wavelength of 1.9GHz is L_{qw}=28.2mm, The microstrip transformer width is given by [41]

$$Z_T = \frac{30\pi}{\sqrt{\varepsilon_r}} \frac{h}{W_e + 0.441h} \qquad \text{Eq.3.9}$$

Effective width of the center conductor is given by [41]

$$\frac{W_e}{h} = \frac{W}{h} - (0.35 - \frac{W}{h})^2 \text{ for } \frac{W}{h} < 0.35 \qquad \text{Eq.3.10}$$

Substituting ε_r=2.2, h=1.72mm and Z_T=112.74Ω we get:

W_{qw}=1.15mm

Another 50Ω transmission line is added to the end of the transformer to connect to coaxial cable. The designed dimension of 50Ω transmission line is L_{50}=5mm, W_{50}=5.24mm.

The final design of the reference MSA is shown in figure 14.

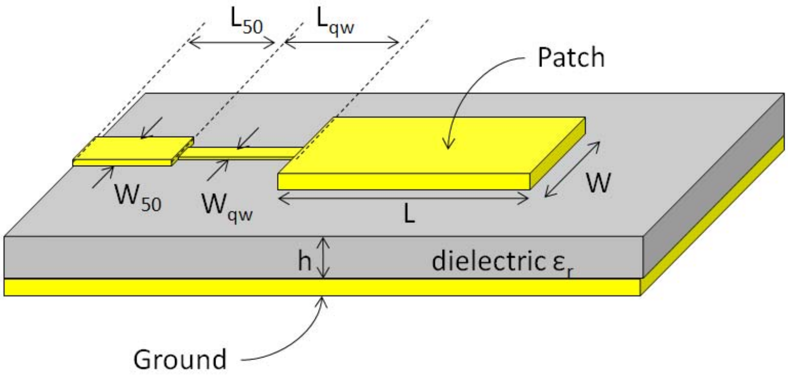


Figure 14. Design of Reference MSA

The summary of the design is shown in table 3.

Table 3. Design Summary of Reference MSA

Microstrip	λ/4 Transformer	Feed Structure	Substrate
W=59.29mm	W_{qw}=1.15mm	W_{50}=5.24mm	W_{sub}=80mm
L=49.75mm	L_{qw}=28.5mm	L_{50}=5mm	L_{sub}=100mm

3.3.2 Antenna Design in Consideration of Geotextile Production Requirement

The design scheme we presented in the previous section is for conventional MSA, which is normally made by photolithography or chemical etching. However, for geotextile antennas, it is not feasible to use these methods of fabrication. It is ideal to integrate the antenna fabrication with the manufacturing process of geotextile. For geotextile material, it is not easy to fabricate a sophisticated transformer matching network. However, the conductive yarn has the potential to be turned into a quarter wave transformer for impedance matching. The antenna's resonant length was already calculated, L=49.75mm. The width of conductive yarn transformer is 2mm. From equation 3.9, Z_T=87.99Ω

According to equation 3.8, the edge impedance of the microstrip is

$$Z_L = \frac{Z_T^{\,2}}{Z_S} \qquad \text{Eq.3.11}$$

Substitute for Z_T=87.99Ω and Z_S=50Ω

Z_L=154.84Ω

Adjust the width of the microstrip to fit this Z_L. From equation 3.7, substitute ε_r=2.2, L=49.75mm, we get W=79.6mm. So the design summary is changed to table 4.

Table 4. Design Summary with Conductive Yarn λ/4 Transformer

Microstrip	λ/4 Transformer	Feed Structure	Substrate
W=79.6mm	W_{qw}=2mm	W_{50}=5.24mm	W_{sub}=100mm
L=49.75mm	L_{qw}=28.5mm	L_{50}=5mm	L_{sub}=100mm

3.3.3 Simulation and Optimization of Reference MSA

The design model of table 4 is loaded in to Ansoft HFSS for optimization. HFSS is a commercial finite element method solver for electromagnetic structures from Ansoft Corporation [40]. The acronym originally stood for high frequency structural simulator. It is one of the most popular and powerful applications used for antenna design. HFSS has a built-in optimizer to calculate and improve antenna performance. The parameters set for optimization include W, L, L_{qw}, and the goal for optimization is set to achieve best resonant at antenna's working frequency. For convenience reason, we name this design as Design 1. The optimized parameters are shown in table 5.

Table 5. HFSS Optimized Parameters for Yarn Feed Design (Design 1)

Microstrip	$\lambda/4$ Transformer	Feed Structure	Substrate
W=88mm	W_{qw}=2mm	W_{50}=5.24mm	W_{sub}=180mm
L=49.7mm	L_{qw}=31.02mm	L_{50}=5mm	L_{sub}=130mm

3.4 Fabrication of Geotextile Antenna

According to the optimized parameters, the reference MSA is fabricated with RT5880 substrate board and adhesive copper foil. Figure 15 shows a comparison of fabricated reference MSA and computer simulation.

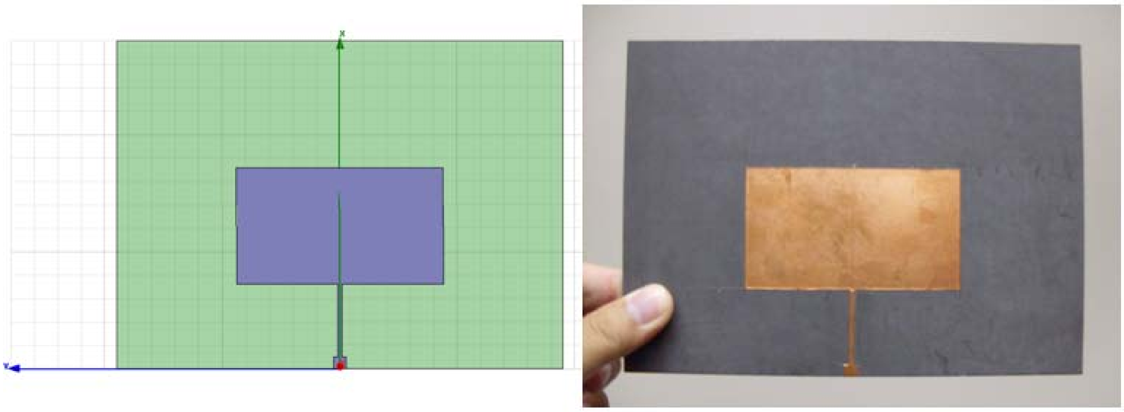


Figure 15. Simulated Model vs. Fabricated Reference Antenna (Design 1)

We assume that geotextile antenna has similar transmission properties as MSA. The prototype geotextile antenna is designed to match the dimensions of the reference antenna. The prototype antenna is made by a sample loom with a plain weave technique. The warp yarn is polypropylene geotextile yarn, and the weft yarn is conductive copper ribbon yarn. The weft is woven side by side to form a fully covered conductive strip to imitate MSA structure. The PP warp yarn in the center of the patch is replaced with a strip of conductive yarn to act as quarter wave transformer and feed structure for SMA connection. A 5.24mm×5mm copper patch is applied at the end of the feed yarn to match the 50Ω impedance of the coaxial cable. We call this structure the full patch for short. A scheme of full patch structure is shown in figure 16. The comparison of fabricated geotextile antenna and reference MSA is shown in figure 17.

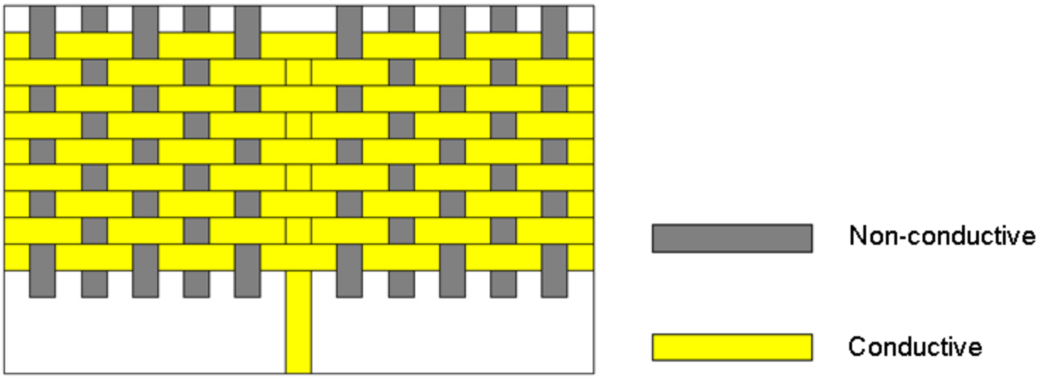


Figure 16. Full Patch Geotextile Antenna Structure (Design 1)

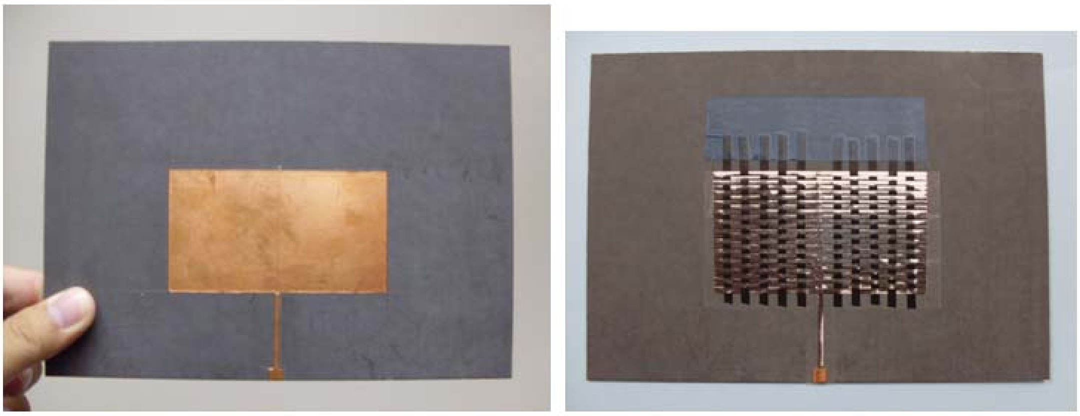


Figure 17. Reference Antenna vs. Full Patch Antenna (Design 1)

CHAPTER 4

TEST RESULTS AND DESIGN REFINEMENT

The antenna characteristics selected for testing are antenna resonant frequency and radiation pattern. The resonant frequency determines whether the antenna will work for the designated band, and the radiation pattern determines the application of antenna e.g. omni-directional for broadcasting or directional for point to point communication.

The simulated RL result of Design 1 is shown in figure 18. Design 1 is optimized by HFSS so that the lowest resonant frequency is at 1.9GHz and the second lowest at 2.2GHz.

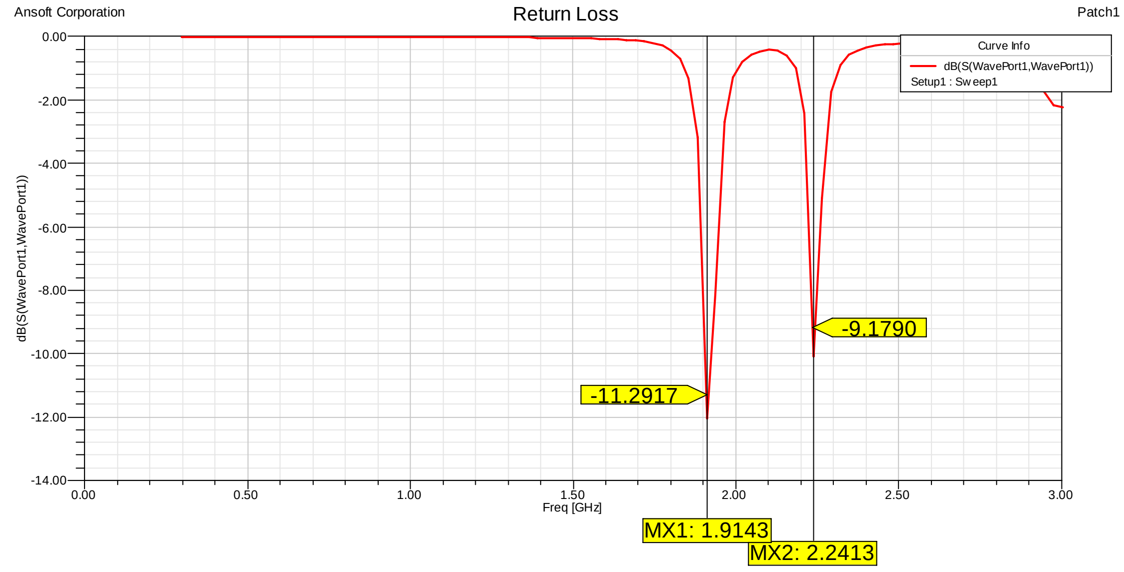


Figure 18. Simulated RL of Reference Antenna (Design 1)

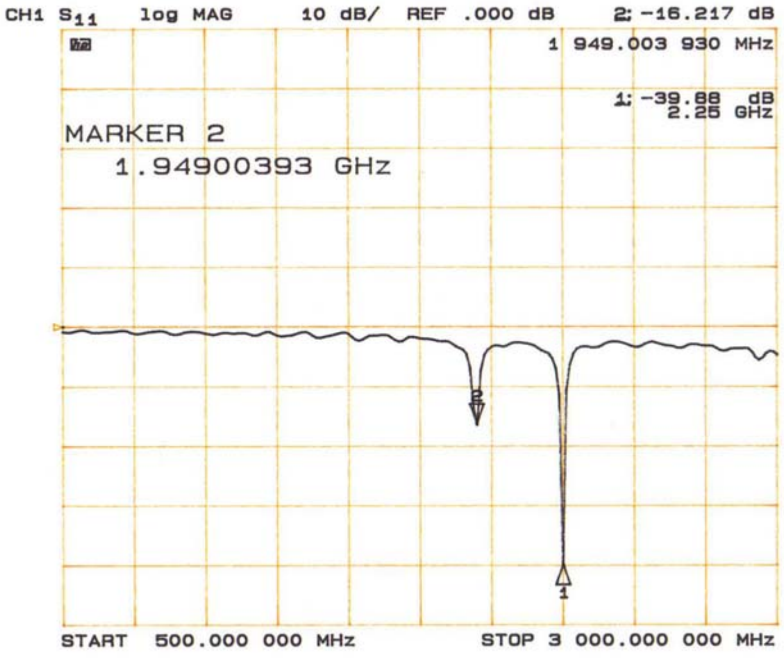


Figure 19. RL of Reference Antenna (Design 1)

The reference antenna is mounted on the HP8753C network analyzer for RL test. Figure 19 shows the RL test result of the reference antenna (Design 1). The resonant frequencies of reference antenna (Design 1) are at 1.95GHz and 2.25GHz. It can be seen that the test result agrees with the simulation.

Figure 20 shows the RL test result of the full patch antenna (Design 1). According to the result, the geotextile antenna exhibits a significantly different resonant property compared to the reference antenna. The lowest resonant frequency is at 700MHz, second at 1.1GHz, third at 2.29GHz, and fourth at 2.54GHz. It can be seen that the 1.9GHz resonant is disappeared in the full patch. However, two lower resonances emerged, and the 2.2GHz resonance remains.

This result indicates the assumption that a geotextile antenna can be predicted by MSA theory is invalid. In order to further study the influence of woven structure on antenna resonant property, a geotextile antenna with alternating conductive and nonconductive yarns was fabricated, designated as half patch (Design 1) for short. The half patch antenna configuration is shown in figure 21.

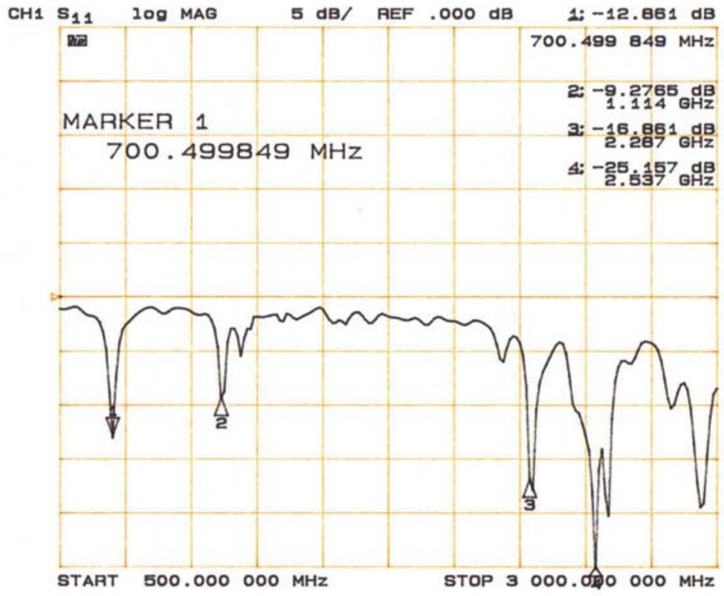


Figure 20. RL of Full Patch Geotextile Antenna (Design 1)

The RL of the half patch antenna is shown in figure 22. It shows that the lowest resonance is at 1.06GHz, and the 2nd lowest resonance is at 2.39GHz.

From the test result of the full patch antenna and half patch antenna, the 1.9GHz frequency which is the target of design for the reference MSA, is not a resonant frequency of geotextile antenna. However, the geotextile antennas and the reference MSA have the same 2.2GHz resonant frequency. This gives us a possibility to shift the target of the design and make the second resonant frequency of the MSA matching the

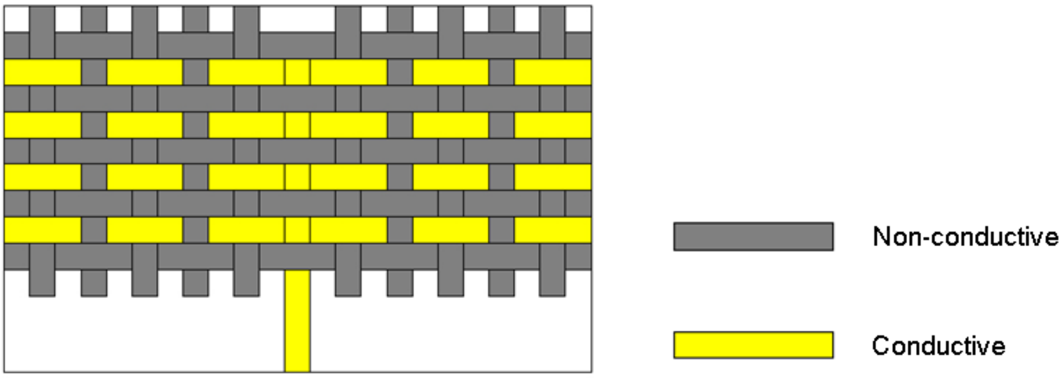
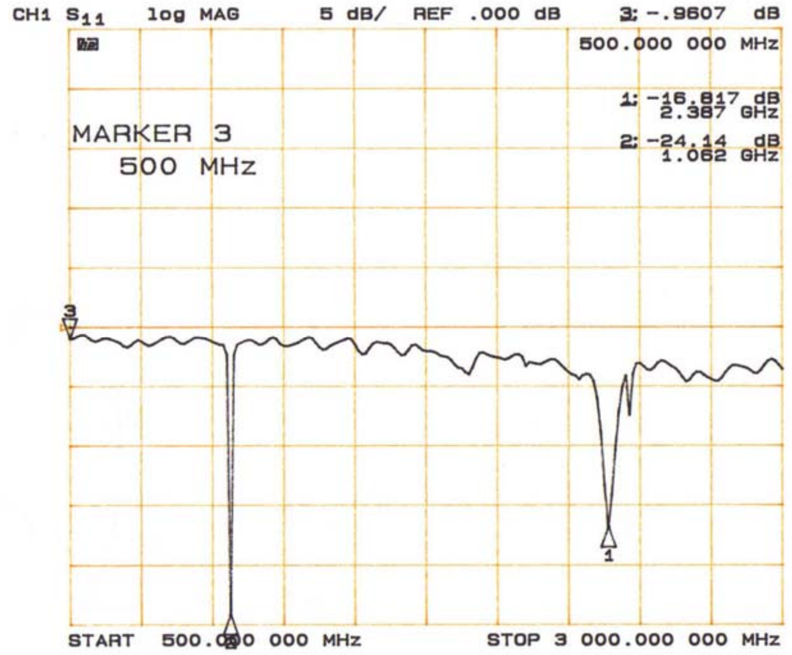


Figure 21. Half Patch Geotextile Antenna Structure (Design 1)



1.9GHz requirement. To shift the second resonance from 2.2GHz to 1.9GHz, the lowest resonant frequency of Design 1 is shifted from 1.9GHz to 1.6GHz. Following the same calculation and optimization procedures of Chapter 3, the refined design (Design 2) parameters are shown in table 6.

Table 6. Refined Design Summary for Frequency Shift (Design 2)

Microstrip	λ/4 Transformer	Feed Structure	Substrate
W=102.7mm	W_{qw}=2mm	W_{50}=5.24mm	Wsub=190mm
L=58mm	L_{qw}=32.9mm	L_{50}=10mm	L_{sub}=140mm

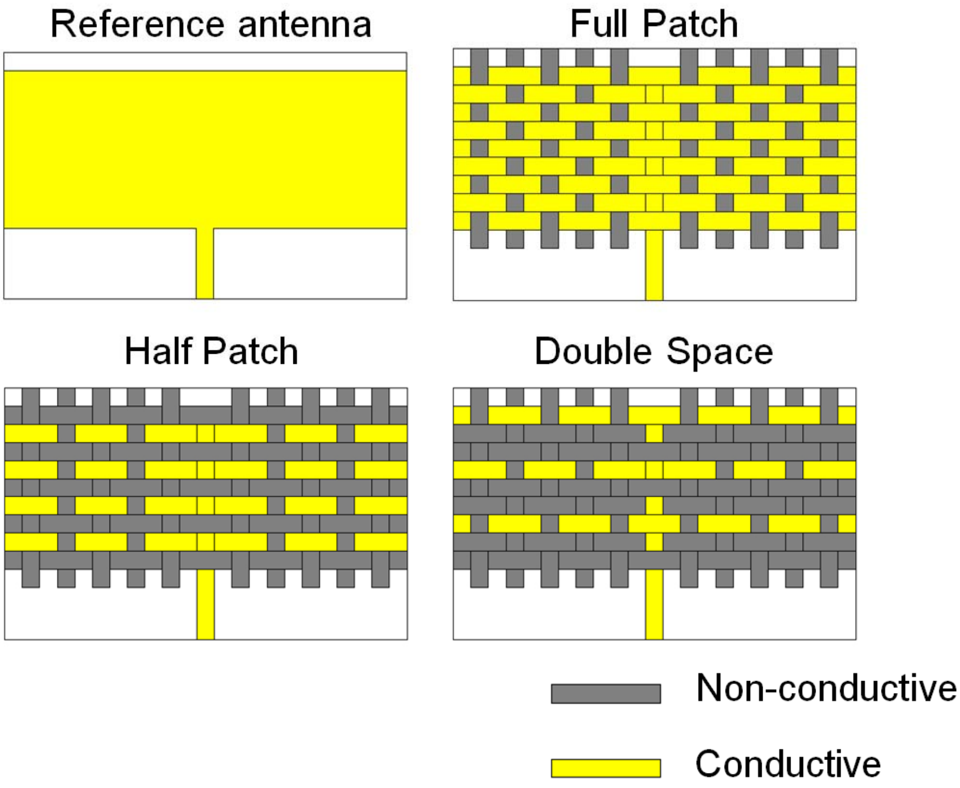


Figure 23. Schemes of Testing Antennas

Furthermore, in order to study the radiation mechanism of the geotextile antennas, we fabricated four antennas, including one reference MSA, and three geotextile woven antennas. The design schemes of the antennas are shown in figure 23, yellow color represents conductive material, and gray color represents non-conductive material. The top left scheme is a reference microstrip antenna. For the geotextile antennas, the warp yarns are geotextile yarns except the very center yarn is replaced by a conductive yarn to serve as a quarter wave transformer and feed structure, and the weft yarns are conductive yarns or conductive/non-conductive alternating weave forming the shape of the radiating element of the microstrip antenna. The top right scheme is a geotextile antenna fully covered with conductive yarns in the weft direction. We name it the Full Patch for short. The bottom left is a conductive/non-conductive alternating weave. We name it the Half Patch because only half of the weft yarns are conductive. And the bottom right is also a conductive/non-conductive alternating weave, but we inserted two non-conductive yarns in between of the conductive yarns, and doubled the spacing between the conductive yarns, so we name it the Double Space. Moreover, the pictures of fabricated antennas are shown in figures 24 through 27 and the RL test results of the antennas are shown in figure 28 through 31.

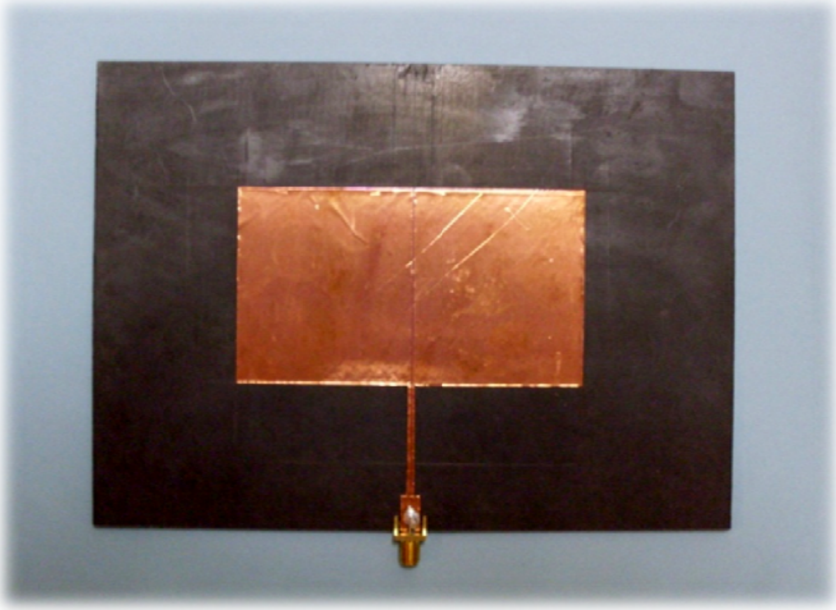


Figure 24. Picture of Reference MSA (Design 2)

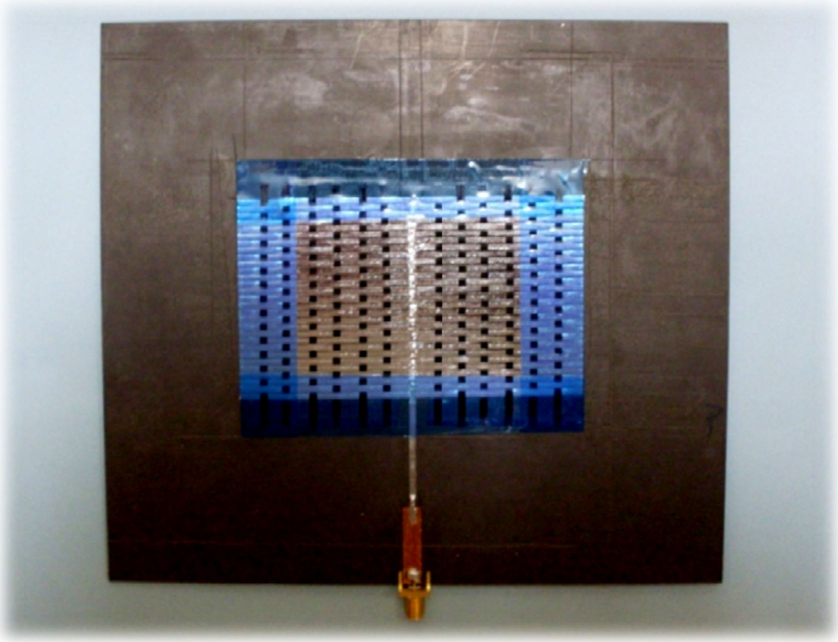


Figure 25. Picture of Full Patch (Design 2)

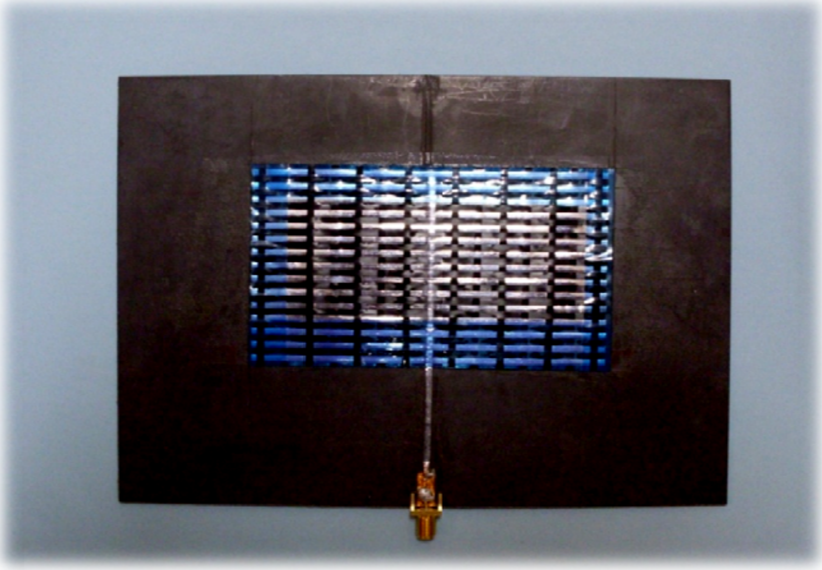


Figure 26. Picture of Half Patch (Design 2)

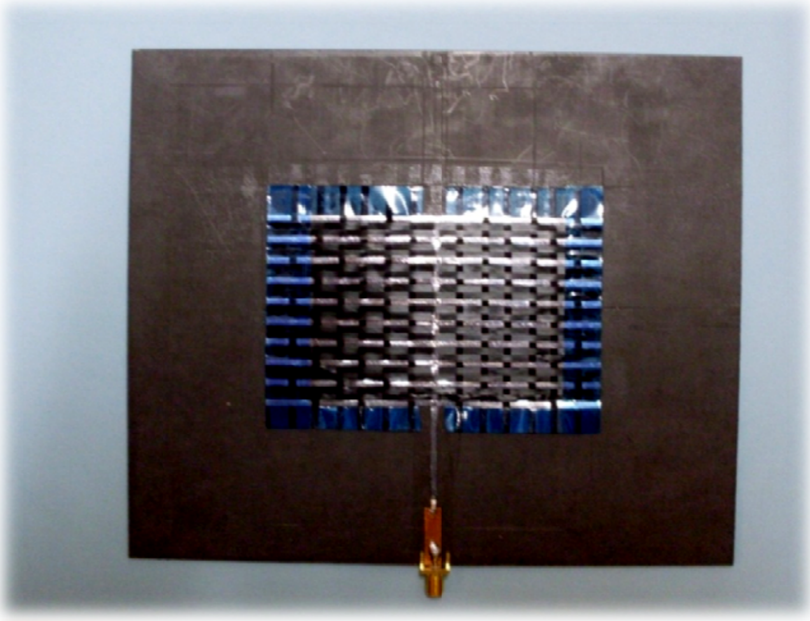


Figure 27. Picture of Double Space (Design 2)

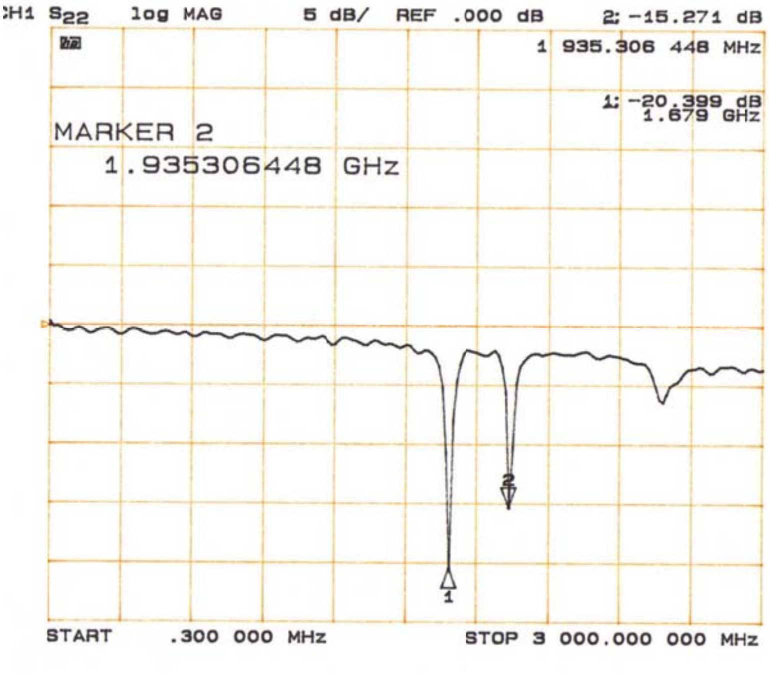


Figure 28. RL of Reference Antenna (Design 2)

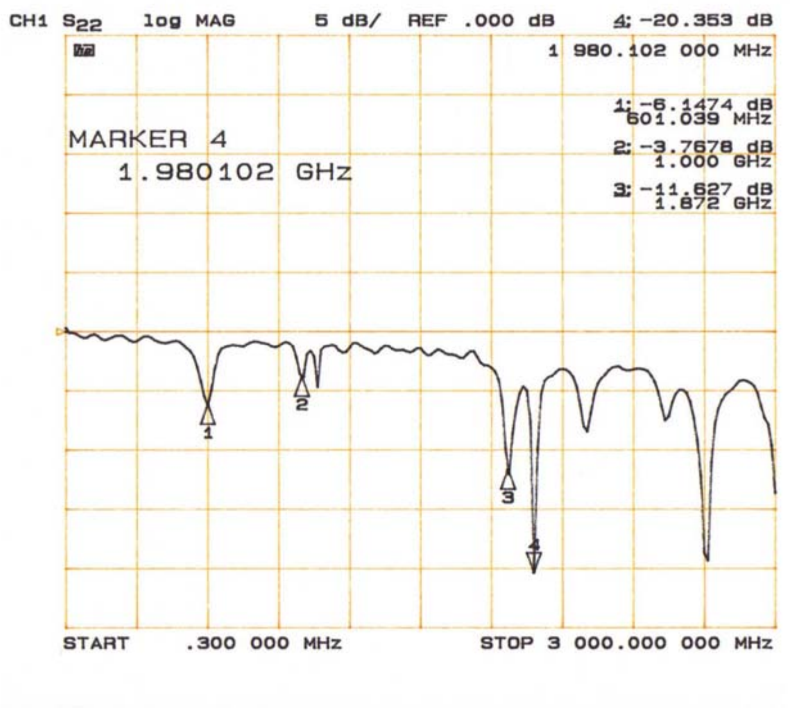


Figure 29. RL of Full Patch Antenna (Design 2)

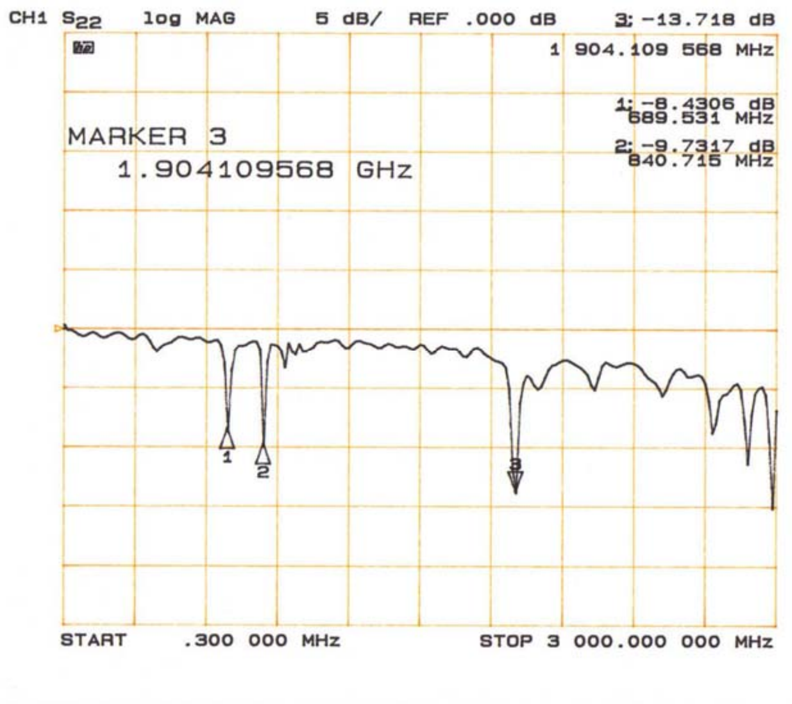


Figure 30. RL of Half Patch Antenna (Design 2)

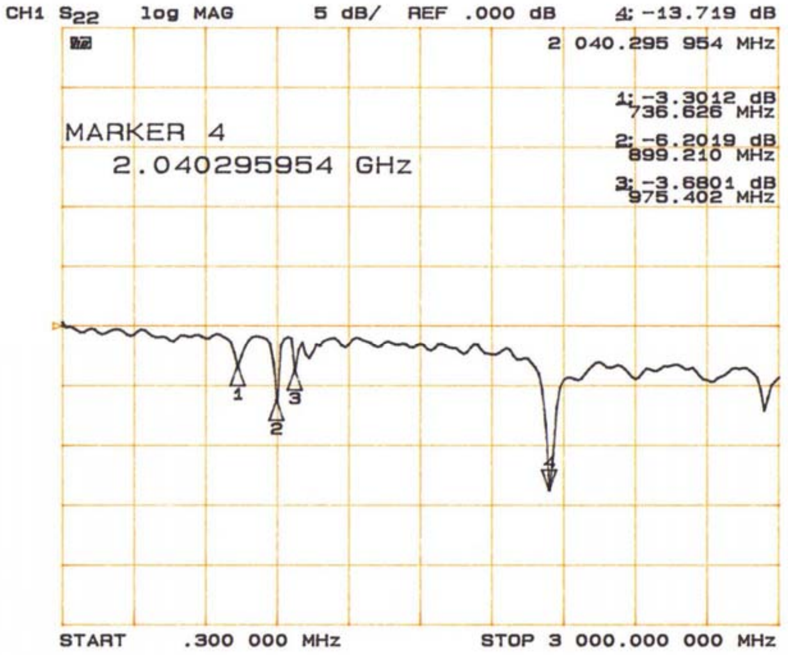


Figure 31. RL of Double Space Antenna (Design 2)

CHAPTER 5

DISCUSSION

In order to study the radiation mechanism of geotextile antennas, first we compare the resonance properties of the geotextile antennas with reference MSA to find out possible corresponding radiation mechanism for MSA resonances. Second, we use simulation software to calculate the surface current of the antennas and the radiation patterns to determine the radiation mechanism of each resonance.

5.1 Geotextile Antenna MSA Radiation Mechanism

The results of Design 1 and Design 2 show that the radiation mechanism of geotextile antenna is different from MSA. For Design 1, as already stated in Chapter 4, the lowest resonant frequency of MSA (1.9GHz) is not present in geotextile antennas. The geotextile antennas are exhibiting resonances at lower frequencies such as 700MHz and 1.1GHz for full patch and 1GHz for half patch.

For Design 2, none of the full patch, the half patch, or the double space geotextile antenna has the lowest resonance of the MSA (1.6GHz). However, for the second lowest resonance 1.9GHz, both full patch and half patch have resonance, and the double space has a shifted resonance at 2.0GHz. This suggests that the woven structure may have disturbed the lowest MSA resonance geometry. The simulation of surface current and radiation pattern of reference MSA at lowest resonance (1.6GHz) is shown in figure 32 and 33. The surface current of reference MSA, full patch, half patch and double space at second lowest resonance (around 1.9GHz) are shown in figures 34 through 41.

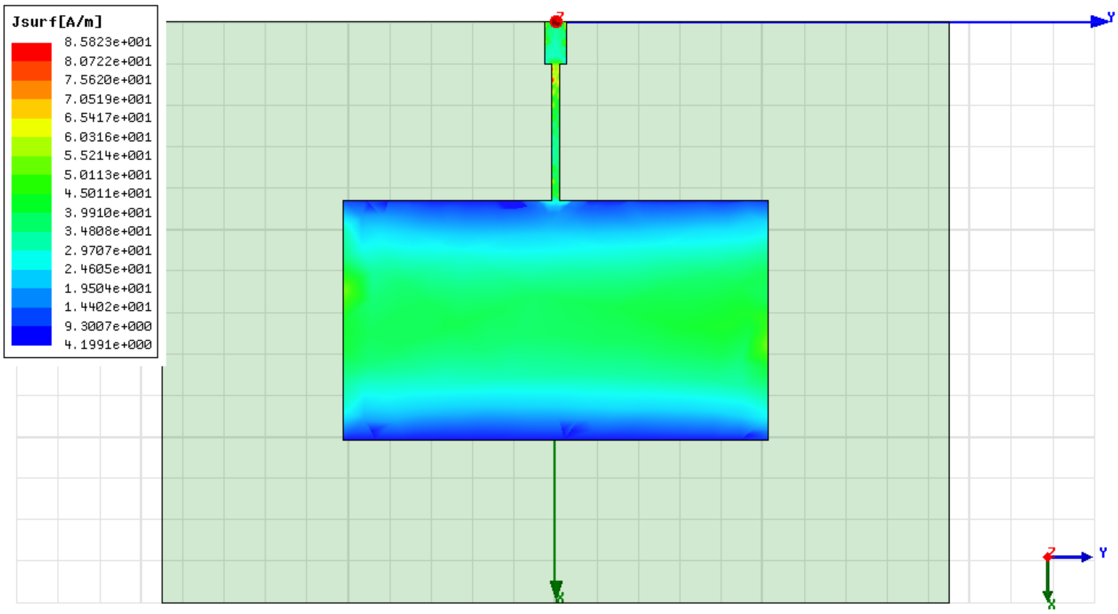


Figure 32. 1.6GHz Surface Current Simulation of Reference MSA

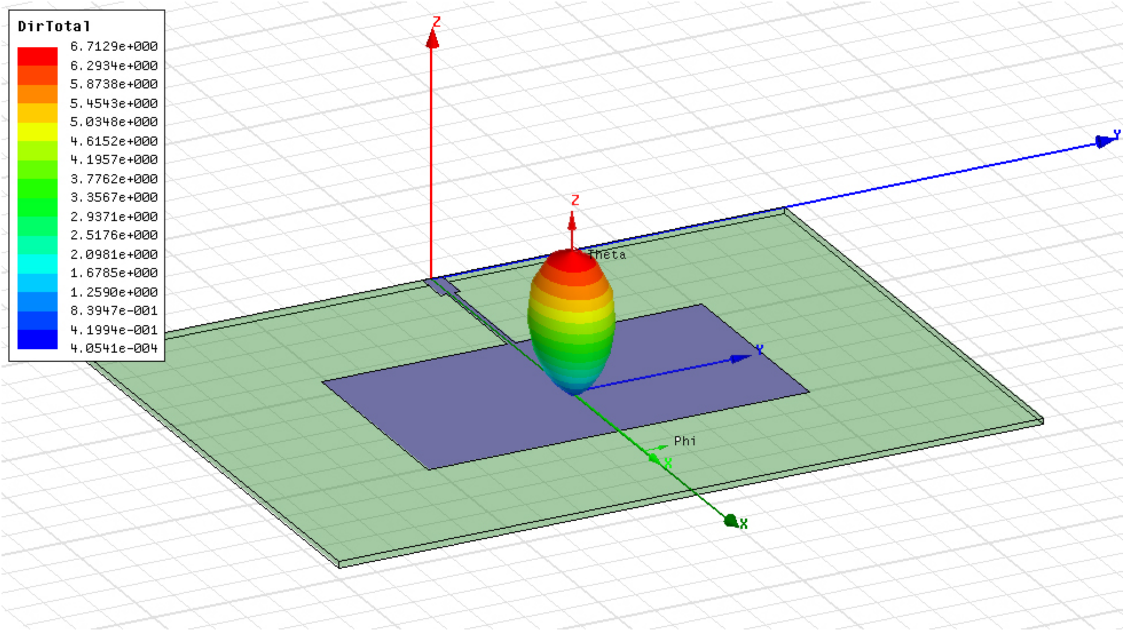


Figure 33. 1.6GHz Radiation Pattern Simulation of Reference MSA

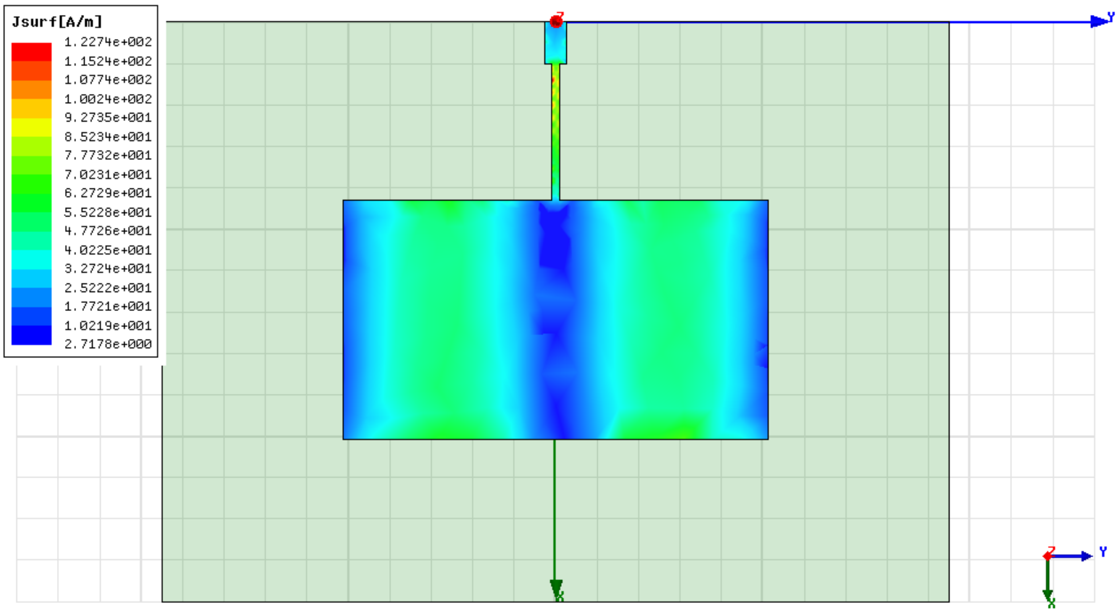


Figure 34. 1.9 GHz Surface Current Simulation of Reference MSA

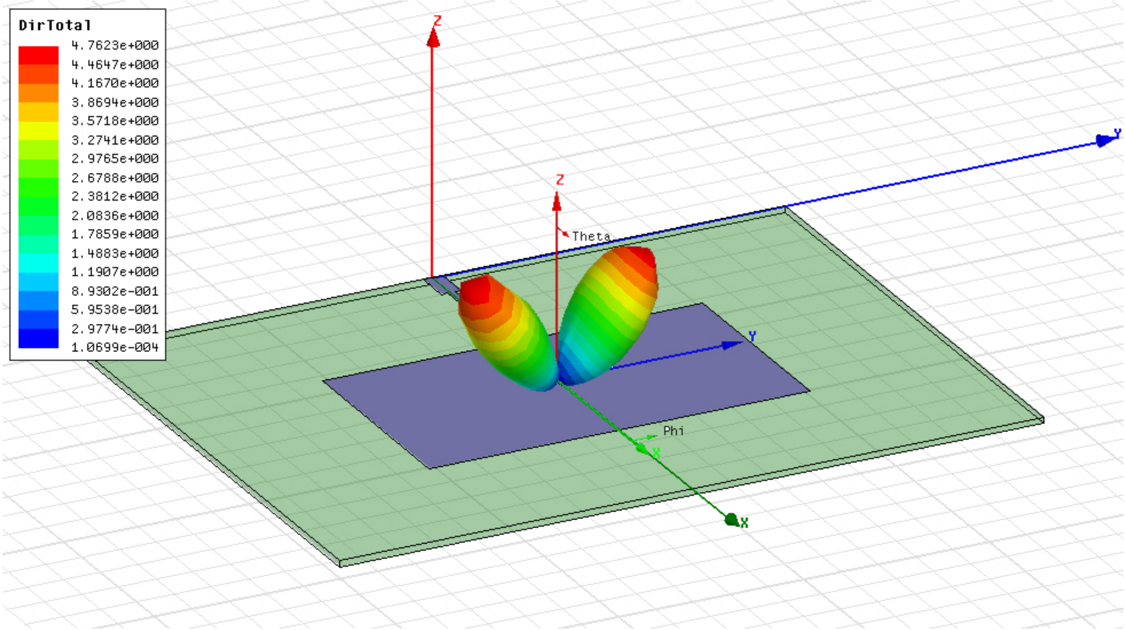


Figure 35. 1.9 GHz Radiation Pattern Simulation of Reference MSA

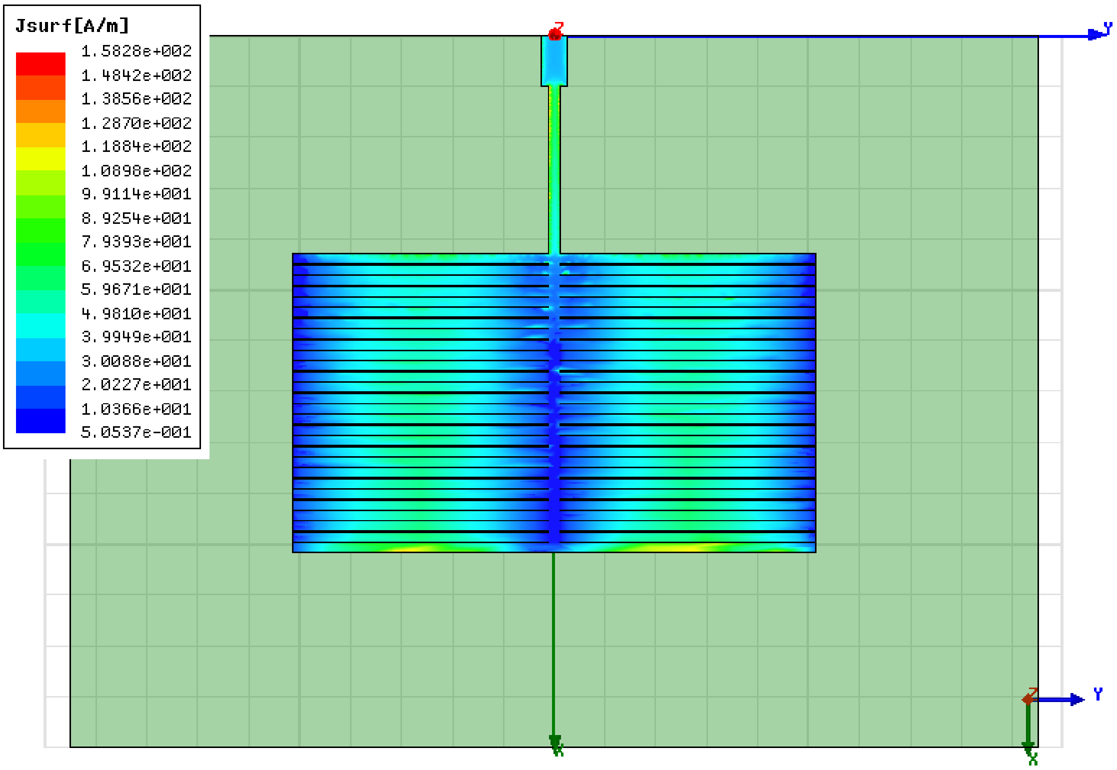


Figure 36. 1.9 GHz Surface Current Simulation of Full Patch

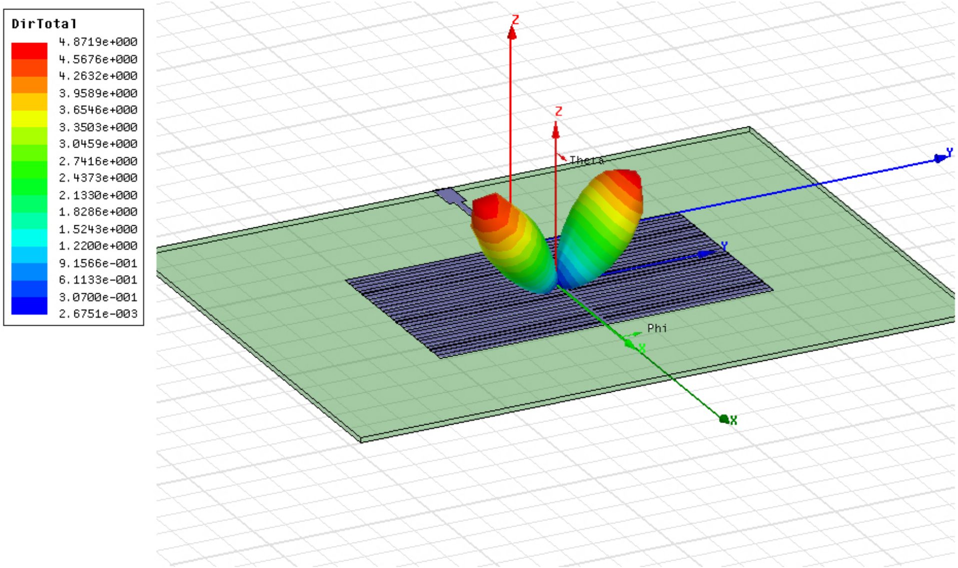


Figure 37. 1.9 GHz Radiation Pattern Simulation of Full Patch

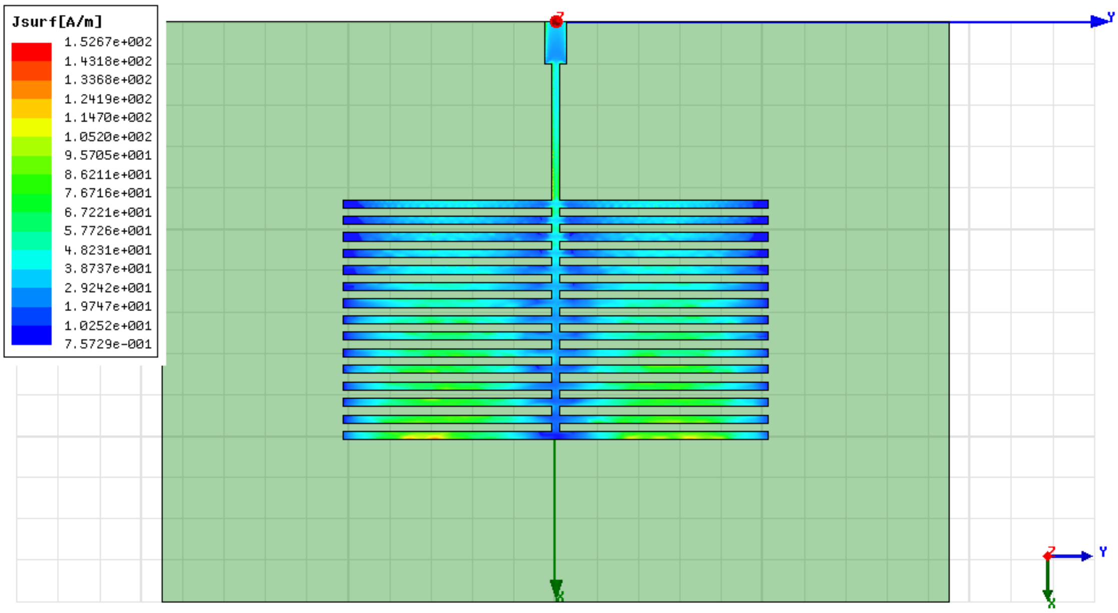


Figure 38. 1.9 GHz Surface Current Simulation of Half Patch

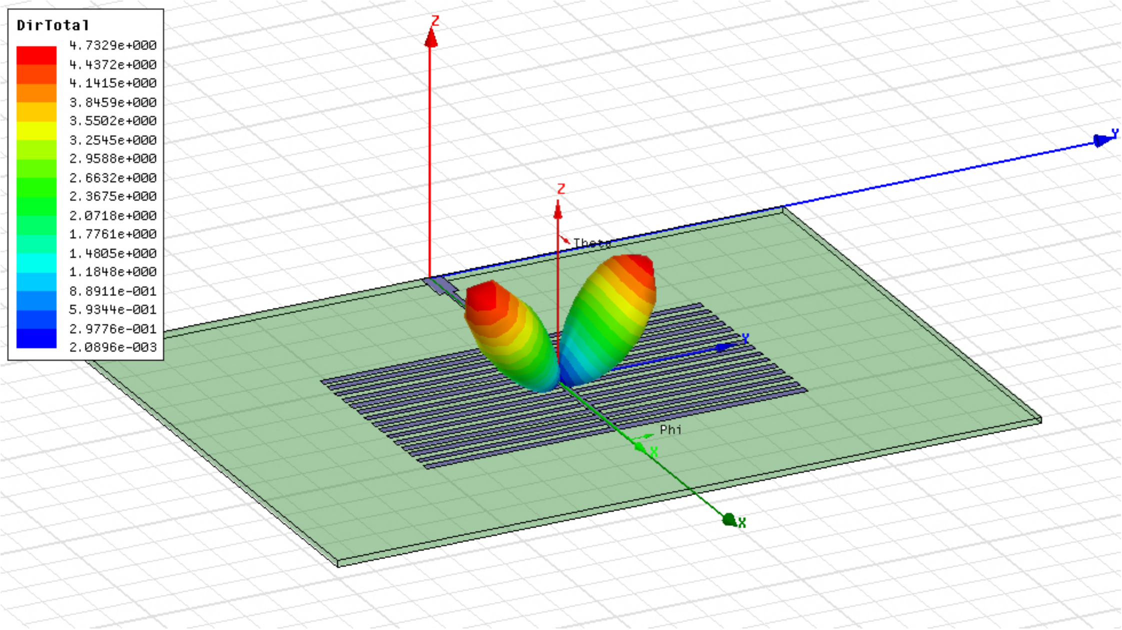


Figure 39. 1.9 GHz Radiation Pattern Simulation of Half Patch

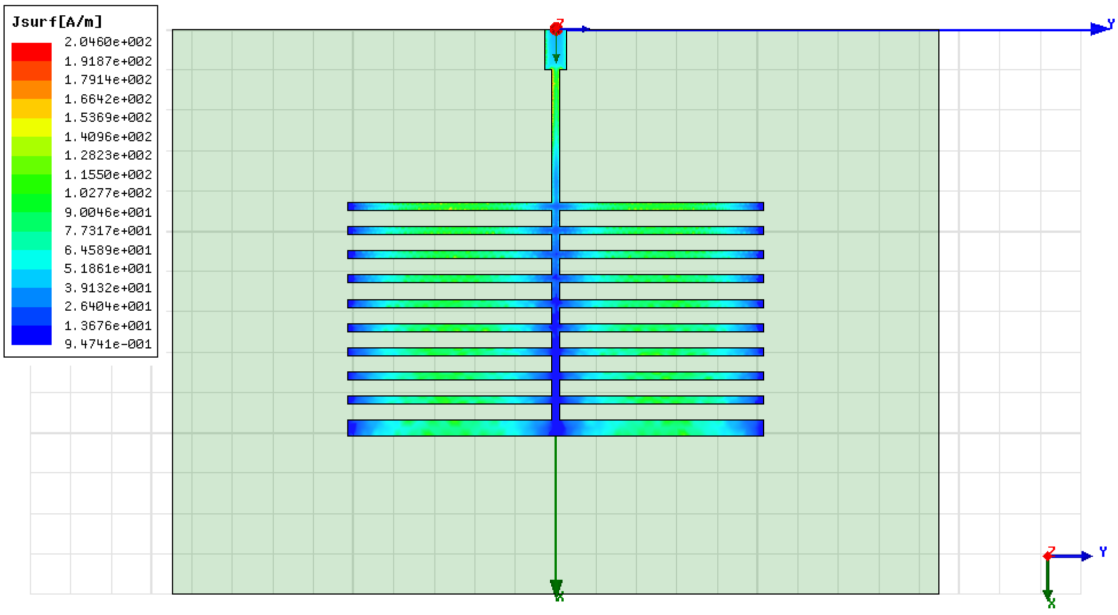


Figure 40. 1.9 GHz Surface Current Simulation of Double Space

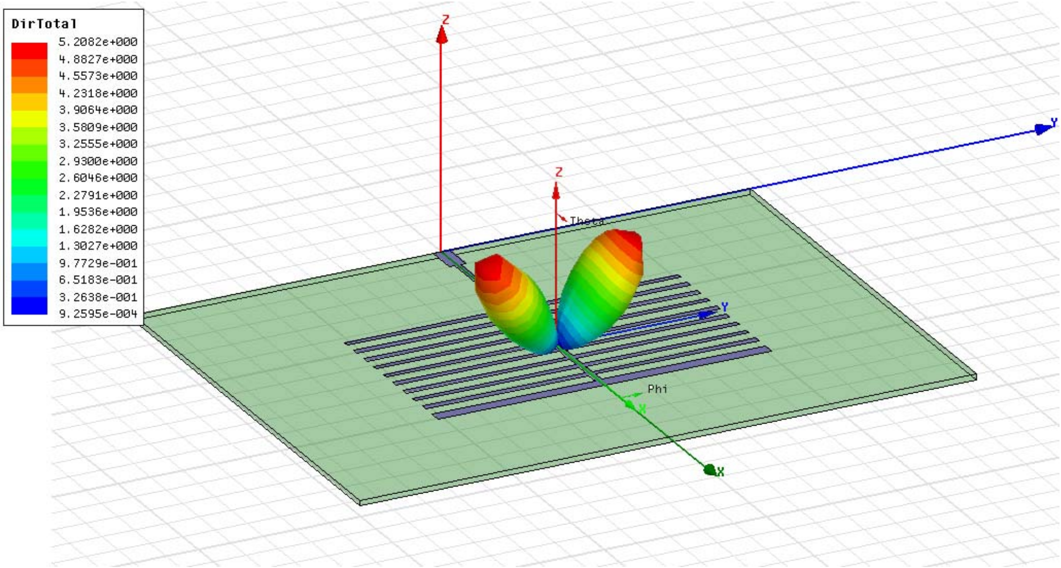


Figure 41. 1.9 GHz Radiation Pattern Simulation of Double Space

The simulations show that the lowest resonance mode (1.6GHz) of MSA is caused by longitudinal surface current, and the second lowest resonance mode (1.9GHz) is caused by latitudinal surface current. For the geotextile antennas, the full patch, half patch and double space have the same resonance mode as the second lowest MSA resonance (1.9GHz). The lowest MSA resonance is not present in the geotextile antennas is possibly because of the woven structure separated the longitudinal continuity of the microstrip, thus prohibited the surface current from flowing in the longitudinal direction. On the other hand, the latitudinal mode is preserved because in this design, the latitudinal continuity of the microstrip is undisturbed. Moreover, as the separation of conductive yarns gets larger, i.e. from full patch to double space, the MSA behavior of geotextile antenna is weakened. As the geometry of the microstrip disturbed furthermore, the geotextile antenna will lose the radiation mechanism of microstrip antenna eventually.

5.2 Geotextile Antenna Dipole Array Radiation Mechanism

As opposed to previous modes, the full patch, half patch and double space have resonances below 1GHz such as 600MHz and 1GHz for full patch, 689MHz and 840MHz for half patch, and weak resonances at 736MHz, 899MHz, and 975MHz for double space. According to MSA theory, the lowest possible resonant frequency for Design 2 is 1.6GHz. This suggests the geotextile antennas have a totally different radiation mechanism for their lower resonances.

The geotextile antennas feature separated conductive strips perpendicular to the feed structure. This structure could possibly make a phased dipole antenna array. The dipole antenna elements of the geotextile antennas have a length of 102.7mm, which is the width of the MSA according to table 6. Using equation 3.4, we can calculate the dipole element's resonant frequency:

$$f_0 = \frac{c}{2L_{eff}\sqrt{\varepsilon_{reff}}} \qquad \text{Eq.5.1}$$

Substituting $L_{eff} = 102.7$mm, $c = 3\times10^8$m/s, and $\varepsilon_{eff} = 2.117$, we get:

$f_0 = 1.003$GHz

This is matching the lower resonant frequencies of the geotextile antennas. According to the impedance match test result, the lower 1GHz resonances are not very strong and have more than one peak. This is possibly due to the irregularity in the geotextile antennas (non-conductive gaps, conductive yarn touching points, and yarn bumps etc.), which rendered the mechanism of lower resonances more complicated and generating more than one resonance frequencies. Moreover, the antenna resonance may also be influenced by the phased array behavior including diversity combining and phase interferences. With all these disturbances, regular dipole antennas array might have might have more than one resonance as well. As a result, half wave dipole array mechanism is a logical explanation of woven antenna resonances at lower 1GHz, which is not a resonant mode predicted by the MSA theory.

5.3 Sample Performance Compared to Geotextile Antenna Requirements

There are two criteria applied to qualify the geotextile antenna for cellular communication network. First, the resonant frequency of the antenna must be in the range of the cellular frequencies assigned by the FCC (see table 2). Second, the RL of the antenna must be less than -9.5dB (-9.5 dB corresponds to a VSWR of 2 which is an acceptable figure for practical application) at the cellular frequencies. With these criteria applied, the applicable bands of the reference MSA and geotextile antennas are shown in figures 42 through 45.

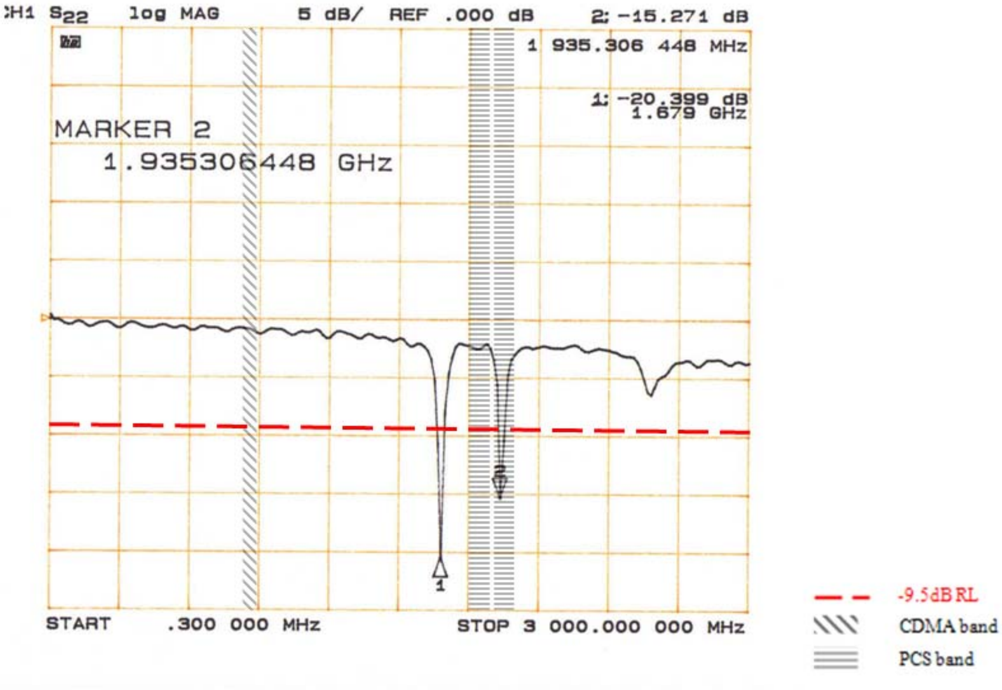


Figure 42. Antenna Performance of Reference MSA

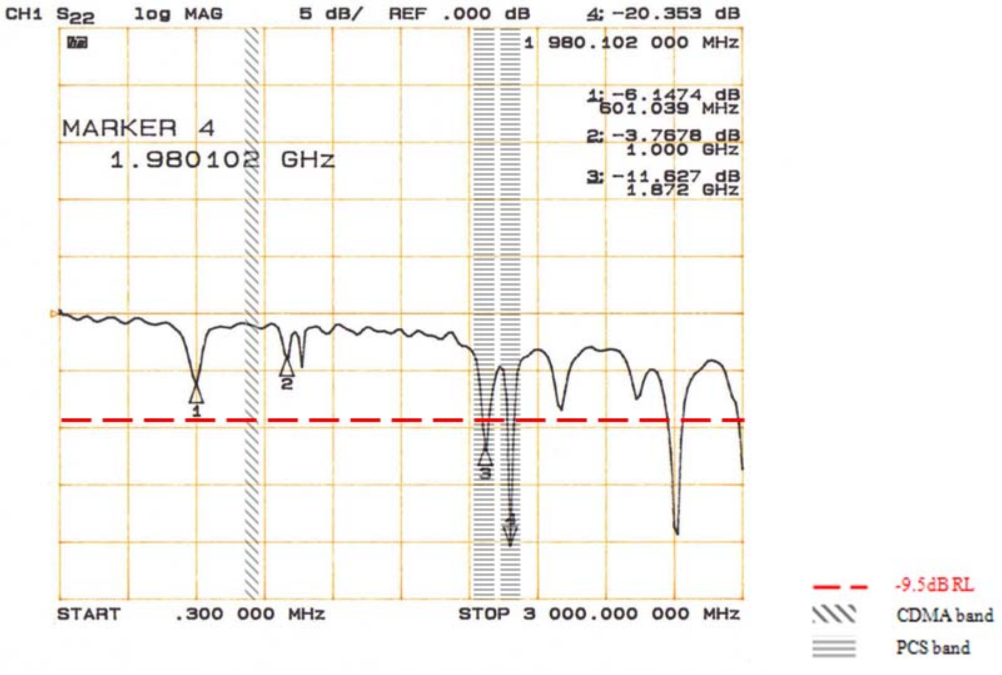


Figure 43. Antenna Performance of Full Patch

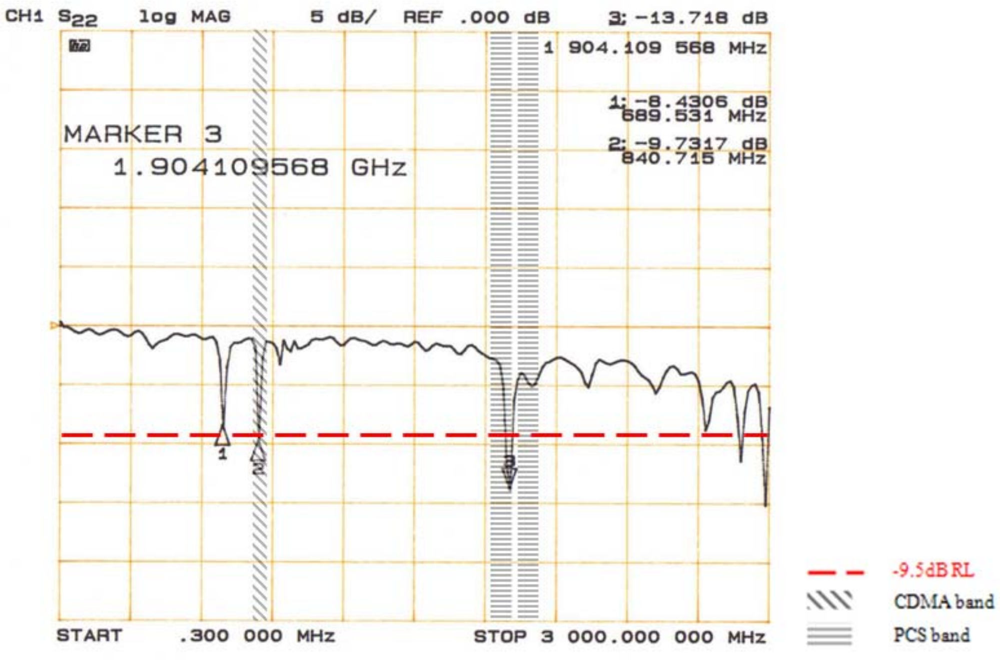


Figure 44. Antenna Performance of Half Patch

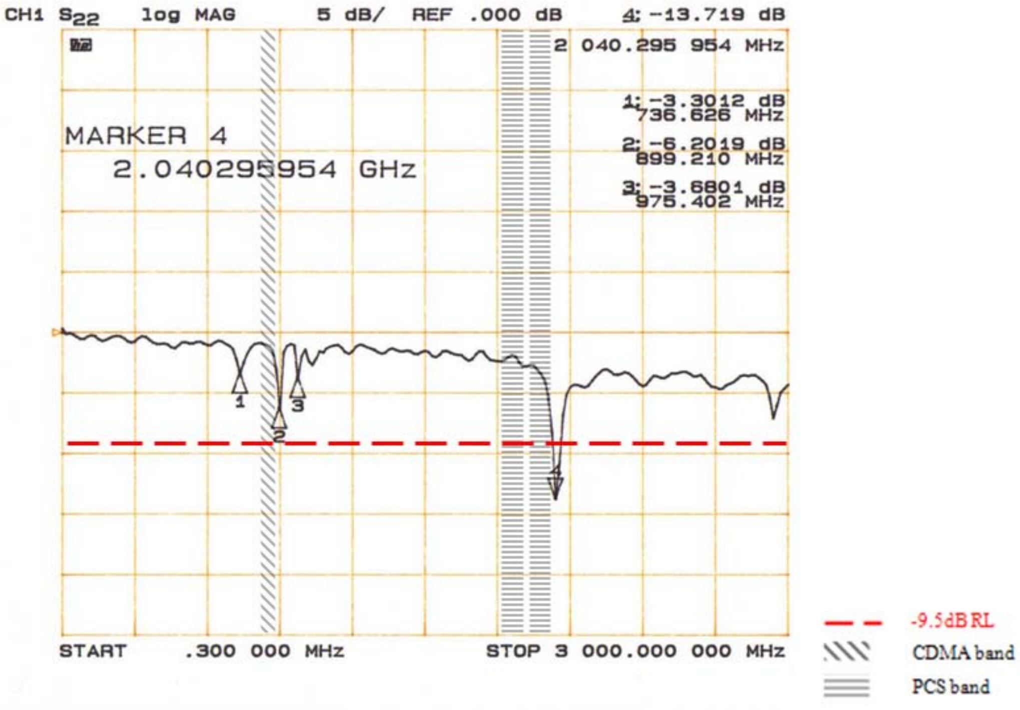


Figure 45. Antenna Performance of Double Space

The red line in the figures represents the -9.5dB RL, and the shaded areas represent CDMA and PCS uplink/downlink bands according to FCC assignment. The figures show that the applicable cellular frequency of reference MSA is 1.94GHz (PCS downlink), of full patch (Design 2) are 1.87GHz (PCS uplink) and 1.98GHz (PCS downlink), and of the half patch (Design 2) are 840MHz (CDMA) and 1.9GHz (PCS uplink). The double space (Design 2) is not qualified for any cellular frequencies.

As a result, the full patch antenna can serve both uplink and downlink PCS band. The half patch antenna and the reference MSA can only serve one link of the PCS band, but the half patch has advantage over the reference MSA on that it can serve CDMA band as well. However the double space antenna cannot be applied to any cellular network.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In this research, by conducting simulation and antenna testing, the radiation mechanism of geotextile antenna is revealed. It is shown that the woven structure of the designed geotextile antenna disturbed the lowest resonant mode of the MSA, but remained the second lowest resonant mode of the MSA. The designed geotextile antennas also possess a resonant mode lower than the MSA modes, which is a result of the dipole antenna array mechanism.

The objective of this research, designing a geotextile antenna that works for PCS cellular band, is achieved. The full patch can serve both uplink and downlink of the PCS band. The research also finds that the half patch can serve the CDMA band as well as uplink of PCS band.

As the radiation mechanism revealed, the next logical step is to further optimize the antenna design. The objective in the near future is to design a relay system with low profile multiband geotextile antenna together with its power source and stand alone connections. The ultimate goal is to incorporate the optimized geotextile antenna relay system into geotextile production and let it serve the wireless communication infrastructure.

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