DESIGN OF A GEOTEXTILE ROADBED ANTENNA

TO CREATE A WIRELESS HIGHWAY NETWORK

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# DESIGN OF A GEOTEXTILE ROADBED ANTENNA

# TO CREATE A WIRELESS HIGHWAY NETWORK

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THESIS ABSTRACT

DESIGN OF A GEOTEXTILE ROADBED ANTENNA

TO CREATE A WIRELESS HIGHWAY NETWORK

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Incorporation of antennas into geotextile fabric to create a roadbed reinforcement with electronic transmission capabilities may find use in expanding communications infrastructures. The design of a model transmission capable fabric and its components are discussed. Signal attenuation resulting from burying these antennas under asphalt was measured. Model antennas were designed and tested using copper tape and a geotextile fabric. A feed structure design was implemented and impedance matching issues were addressed.

Measurements of antennas constructed using copper tape indicated that antennas properly woven into roadbed fabric should perform adequately. Proposed efforts to create an electronic transmission capable roadbed with woven conducting components are discussed.

## ACKNOWLEDGMENTS

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The thesis document was typed using MS Word 2003 with drawings created in MS PowerPoint. Experimental results were measured with Diamond Engineering's Antenna Measurement Studio and analyzed in MATLAB.

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# CHAPTER 1

# INTRODUCTION

The past couple decades have brought a major revolution in how people are connected, inciting a global environment in which ideas and information are freely and easily exchanged. This increase in connectivity has been—and will continue to be—dependent on creating and improving communications infrastructures [1, 2]. With major technological advances with networks like the internet, cellular phones, and GPS (Global Positioning System), the world is more connected than ever before.

However, even the most advanced networks have their limitations. In fact, many communications providers have struggled to find an inexpensive solution to the problem of getting their services to the customers' homes [3]. Known as the last mile, this difficulty has proven to be quite expensive as the price of laying copper or fiber optic cable can be costly. Many providers are turning to wireless networks as a solution to the last mile problem [4, 5].

Cellular networks, too, have their limitations. The two main public complaints about cell towers are that they produce excessive radiation and that they are unattractive [6]. From a communications service provider's perspective, cell towers are expensive and can be impractical to assemble. In extremely uneven terrain, such as mountainous regions, it is difficult to place a tower. Also, in rural areas, the cost of putting up a tower often outweighs the revenue that would be generated by the limited number of customers in the coverage area. This leads to incomplete coverage, which is unacceptable in today's information age. Furthermore, because of their large size and exposed elements, cell towers are susceptible to damage from adverse weather, such as hurricanes and lightning strikes. If a tower is extensively damaged it would likely require costly repair and the entire coverage area could lose service [7, 8].

Even the GPS network has its pitfalls. Currently, one of the most common uses for GPS is vehicle tracking and navigation. Any car with the proper GPS navigation equipment can get directions to a desired location, provided the destination is programmed into the system. However, the accuracy of the car's displayed position can be off by anywhere between a few feet and 300 feet, depending on various factors that are uncontrollable by the user (relative position of satellites, weather conditions, multipath fading, propagation delay, receiver noise, etc.) [9]. This level of accuracy is sufficient for present navigation purposes, but future navigation systems in the information age will demand a greater degree of precision. By connecting cars on a WLAN (wireless local area network), they can be given an awareness of each others' positions as well as their own, allowing for real-time traffic information that automatically calculates the fastest route to a destination [10]. Additionally, an algorithm can be written that uses this data to prevent collisions, similar to what's already being done with robots [11]. Both of these applications would require a much higher level of accuracy than what is currently offered by the present GPS network.

The problems of the last mile, inadequate cell coverage, and automobile navigational limitations due to GPS inaccuracy can all be improved by developing a communications network built into the nation's roads. A WLAN could be created by periodically burying antennas, or access points, underneath the roads. This type of network would be a low cost solution to the problem of the last mile by providing service anywhere there is a road. The roadway access points could also be used to supplement cell towers, expanding the cellular network to areas that are presently not covered, either because of physical or economical constraints. The network's antennas would be shielded by the asphalt, offering protection from harsh weather. And finally, the roadway WLAN would be able to accurately monitor the position of every car on the network, providing real-time traffic information while allowing cars to communicate with each other.

To maintain a low cost and ease of installation, it is desirable that the antenna access points as well as the transmission line feeding structure of this network be woven into the geotextile roadbed beneath the asphalt. In doing so, the construction process of laying a new road (or resurfacing old roads) is unchanged and the network naturally develops with the expansion and maintenance of the roads.

This paper presents the concept and design process of constructing an electronic transmission capable roadbed, which could be used to create such a WLAN buried under the nation's roads. The topics of signal attenuation from transmitting through asphalt, weaving antennas into the geotextile roadbed, designing a feed structure, and system impedance matching are discussed. Experimental results are given where appropriate.

# CHAPTER 2

# BACKGROUND AND OBJECTIVES

When a new road is constructed, a roadbed fabric, or geotextile, is laid before the asphalt is poured. This geotextile can serve several purposes, such as reinforcement, separation, filtration, drainage, erosion control, sediment control, and waterproofing [12]. The widespread use of geotextiles in road construction and maintenance presents a unique opportunity for the roadbeds to become part of the nation's communications infrastructure. Using conductive threads, antenna and transmission line structures can be woven into the geotextile fabric, creating roadbeds that not only reinforce the asphalt, but also serve as access points along a national wireless network.

However, creating a roadbed capable of transmitting through the road to above ground receivers involves investigation into several areas. The first phase of the research was devoted to proving the concept was possible. This was done by examining signal attenuation through a layer of asphalt and attempting to construct functional antennas using geotextile material as a chief component. If the signal was completely reflected or attenuated by the asphalt, then it would not be possible to transmit through the road. Similarly, if the properties of the geotextile material behaved in such a way as to prevent effective radiation, then antennas woven into the roadbed would not radiate. Both of these concerns needed to be resolved before pursuing further research. After demonstrating proof of concept, more specific details, such as antenna type, feed structure, and impedance matching are addressed. The major contribution of this work is a proposed design for an electronic transmission capable geotextile roadbed, which can be used to expand the communications infrastructure in this country and others.

CHAPTER 3

# TRANSMISSION THROUGH ASPHALT

Two experiments were conducted to examine the power loss associated with transmitting through a road-sized thickness of asphalt. The first experiment involved burying an antenna in the ground and then covering it with a slab of asphalt, measuring 2' x 2' x 3". The received signal strength was measured 50 ft. away by an above ground antenna with and without the asphalt slab covering the buried antenna. The resulting power loss was computed by subtracting the received signal strength of the uncovered case from the same for the covered case.

The first experiment was carried out assuming that the slab of asphalt was large enough to approximate the effect of an entire road. The second experiment tested this assumption by actually burying the antenna under a standard size asphalt road. The results of both experiments were analyzed to gain a better understanding of RF signal attenuation due to an asphalt road.

## 3.1 Equipment Used

In order to maintain consistency for comparison between the two experiments, the same equipment was used in each. Only the asphalt covering the transmitting antenna was changed between the two experiments. Each test included a source, consisting of a signal generator and source antenna, and a receiver, consisting of a spectrum analyzer and receiver antenna. The source and receiver antennas in Fig. 1 were identical circular patch antennas that operated at 912 MHz.

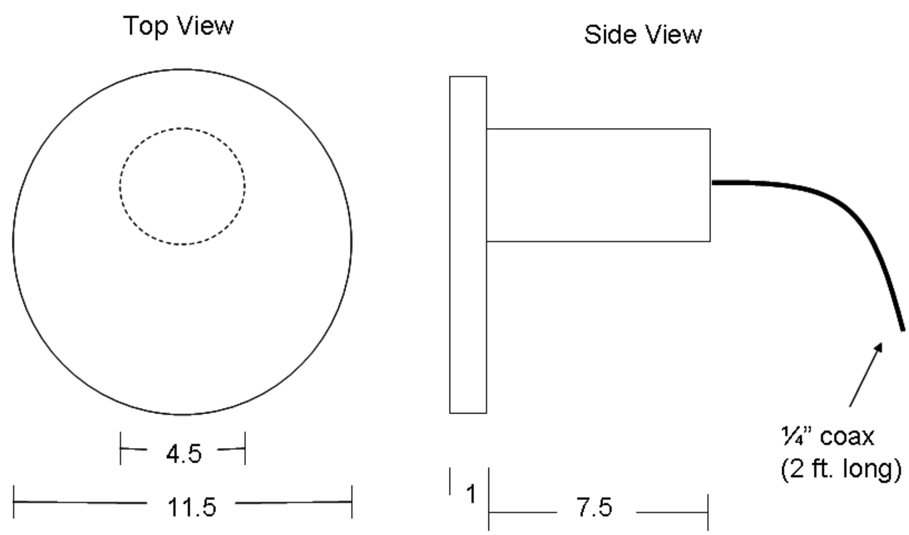


**Figure 1**—Source and receiver antenna dimensions in centimeters

The antenna pattern and polarization characteristics (which are discussed in detail in the next section) were observed during the first experiment.

### 3.2 Experimental Procedure and Results

The procedure outlined in Fig. 2 was used in each experiment to determine the attenuation of a signal through a layer of asphalt of typical road thickness.

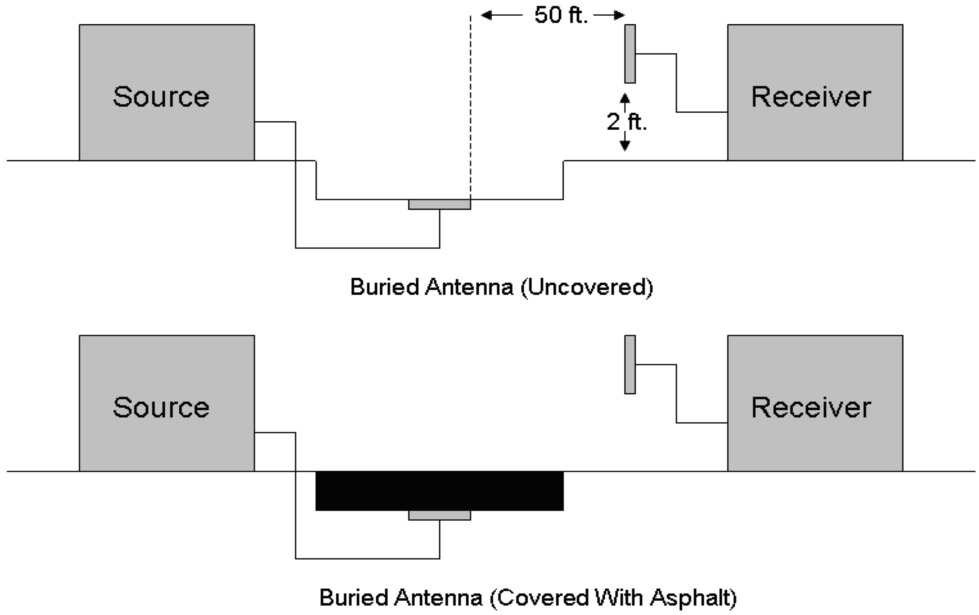


**Figure 2**—Asphalt attenuation experiment setup

The source antenna was buried so its top (radiating) conductor was flush with the underside of the asphalt layer when covered. When it was uncovered, the top conductor was open to air. A 1 mW signal was produced by the signal generator for transmission from the buried source antenna. The received signal level was measured by the spectrum analyzer via the receiver antenna, which was 50 ft. away from the source antenna. The received signal level was recorded first with the source antenna uncovered, and then again with it covered by asphalt. The difference in the received signal levels is the power loss associated with burying the antenna under asphalt. Signal loss is due to the attenuation and reflection of the signal by the asphalt slab.

The received signal level varied with different orientations of the source and receiver antennas. It was therefore imperative to know the antennas' radiation pattern and polarization characteristics to maximize the signal transfer. The radiation patterns of the antennas were observed by holding the source antenna in place and rotating the receiver antenna. This was repeated for multiple well-chosen orientations of the source antenna. A maximum received signal level occurred when the antennas' top conductors faced each other. A null occurred when the edge of one (or both) of the antennas faced the other. The radiation pattern of the antennas was then determined to be a figure-8 pattern with the main lobe perpendicular to the axis of the antenna, a small back lobe in a direction opposite to that of the main lobe, and nulls in the edge direction. This pattern was later verified by more precise measurements with specialized equipment.

The antennas were also observed to be linearly polarized. This was observed by facing the antennas top conductors directly at each other (at a maximum in their radiation patterns) and rotating the receiver antenna about the axial direction. The received signal level was very sensitive to the polarization, achieving a maximum when the feed points (which are slightly off center) were aligned.

In order to receive the largest signal possible, the receiver antenna was oriented so its top conductor pointed directly to the source antenna and was rotated to achieve polarization alignment with the source antenna. The receiver antenna was also raised 2 ft. from the ground in order to avoid a null in the radiation pattern of the source antenna. This gave more reliable results and was also a good indication of antenna performance when mounting a receiver antenna on an automobile.

### 3.2.1 Experiment 1: Antenna Buried Under Asphalt Slab

In the first experiment to determine the effect of burying an antenna underneath the road, a square asphalt slab was used as an approximation of the road. As indicated in Fig. 3, a trench the size of the slab was dug and the antenna was buried so that its top was flush with the bottom of the hole.

**Figure 3**—Buried antenna (uncovered) and signal generator

Next, Fig. 4 shows the antenna covered by the asphalt slab so there was intimate contact between the antenna and asphalt. Finally, measurements were taken in accordance with the previously described procedure.

**Figure 4**—Buried antenna (covered by asphalt slab) and signal generator

With the antenna uncovered, the received signal level was -63.3 dBm. When it was covered by the asphalt slab, the received signal level dropped to -67.3 dBm, indicating a 4 dB loss due to the slab. Before the test, there was concern that the asphalt could completely block the signal. After measuring only a 4 dB loss, we wondered if the 2’ x 2’ x 3” slab adequately approximated the situation when the antenna was placed under the middle of a standard width asphalt highway. We conjectured that the signal may be radiating from the edges of the slab rather than through it. In order to investigate the matter further, we decided to repeat the test with the antenna buried under a standard size asphalt road.

### 3.2.2 Experiment 2: Antenna Buried Under NCAT Test Track

For the second experiment, it was necessary to find a test site where an existing road could be dug up to bury the antenna. Experiments were carried out at the NCAT (National Center for Asphalt Technology) test track [13].

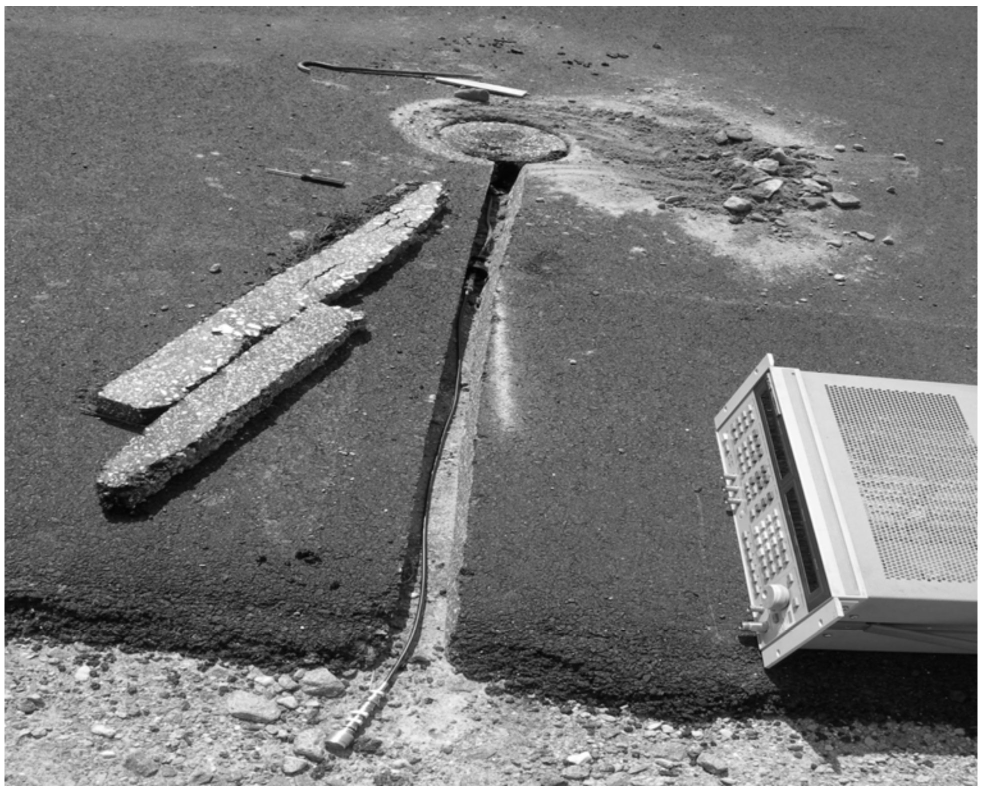

**Figure 5**—Asphalt hole and trench at the NCAT test track

To bury the antenna, an 8 inch diameter plug was cut from an existing road. Fig. 5 shows a trench that was cut from the hole to the side of the road to allow the cable from the signal generator to the antenna to also be buried. The antenna was then buried in the hole in the road and covered with the asphalt plug, as shown in Fig. 6.

**Figure 6**—Source antenna covered by the asphalt plug

This way, when the antenna was covered by the plug, it was in fact buried by an entire road. Finally, in Fig. 7, measurements were taken following the same procedure as previously described.

**Figure 7**—The received signal level is measured for the covered case

When the antenna was uncovered, the received signal level was -65.5 dBm. When it was covered by the asphalt plug, the received signal level dropped to -73.5 dBm. This indicates an 8 dB power loss associated with burying the antenna under a road. Though the loss was greater in the second experiment (which was expected), it was still a much lower loss than anticipated. Even with the 8 dB loss from burying the antenna underneath the road, we were still able to transmit successfully to an above ground receiver 50 ft. away using only 1 mW of transmitting power. Thus, it was determined that the asphalt would not be a significant limiting factor in attempting to develop geotextile roadbeds with electronic transmission capabilities. Since it appeared that transmission through asphalt was indeed feasible we next directed our research efforts toward integrating the antenna with the geotextile roadbed material.

# CHAPTER 4

## ANTENNA CONSTRUCTION WITH ROADBED MATERIAL

Because the proposed design called for antenna structures woven into the geotextile roadbed, it was necessary to ascertain whether or not antennas could be effectively constructed with the roadbed material. Fabric-based antennas are a relatively new field, with the majority of their applications being used for electronics and wireless communications sewn into clothing [14-16]. As with conventional antennas, the materials used for a fabric antenna's conductive and nonconductive components plays an important role in its performance [17, 18]. However, fabric-based antennas have an important additional design consideration; namely how the conductive threads that define the antenna are woven into the textile material [19]. It was therefore paramount that the geotextile fabric be thoroughly examined as a potential building block for antennas.

Multiple antenna designs were built using the roadbed material as a dielectric substrate. These roadbed antennas were then compared to theoretical conventional antennas of the same type (dipole, microstrip patch, etc.). The performance was compared on the basis of two different measurements: voltage standing wave ratio (VSWR) and radiation pattern measurement. Ultimately, measurements indicated that antennas could be constructed from the roadbed material that performed as well as conventional antennas.

### 4.1 Antenna Types

Choosing the appropriate antenna type was an essential part of the design of the transmission capable roadbed. From a manufacturing standpoint, the antenna had to be a structure that could be easily woven into the geotextile material. Furthermore, from an electronics point of view, it was imperative that the antenna exhibit the proper radiation characteristics. Care was taken to examine multiple antenna types and choose the one that would meet all design constraints.

#### 4.1.1 Microstrip

The first roadbed antennas designed were microstrip patch antennas. This type was chosen because it is a simple geometry to create and is easily fed by a microstrip transmission line.

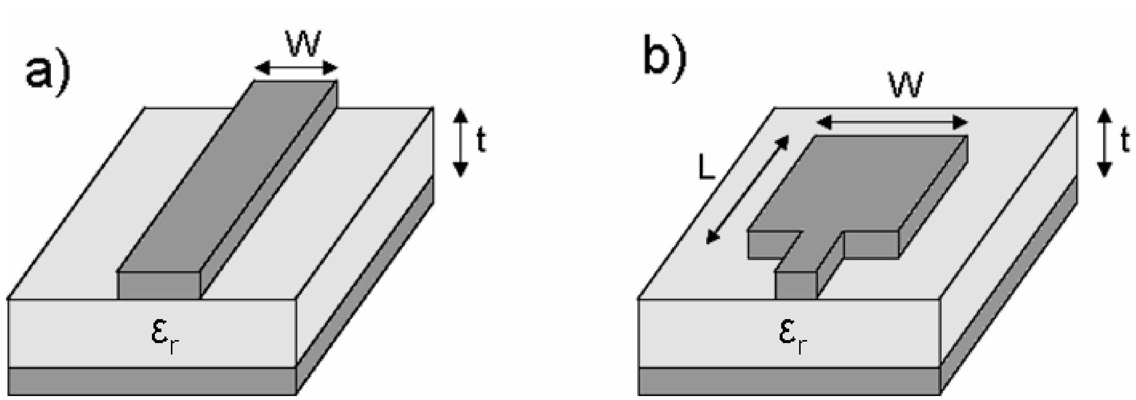


**Figure 8—**Geometry of a microstrip a) transmission line, and b) rectangular patch antenna

The impedance of the microstrip transmission line in Fig. 8(a) is defined primarily by the relative permittivity of the dielectric substrate and ratio of the signal line width to the substrate thickness. Hence, the impedance can be accurately set by choosing appropriate values for the signal line width and substrate thickness for a given substrate material [20]. The same parameters define the input impedance of the rectangular microstip patch antenna in Fig. 8(b), which is an important consideration when impedance matching for maximum power transmission [21].

The rectangular patch antenna is usually designed such that the length, L, is approximately a half wavelength at the operating frequency (the length is usually reduced slightly to compensate for the fringing fields at the patch edges, which extend the effective length of the antenna). Also, taking into account the effect of dielectric substrate, the length is chosen as

$$L = .49 \frac{\lambda}{\sqrt{\varepsilon_r}}$$

where $\lambda$ is the wavelength in free space and $\varepsilon_r$ is the relative permittivity of the dielectric substrate [21].

The ease of design and construction of patch antennas make them very popular. However, if the antennas and feed structure are woven into the roadbed material, they would have to be a planar design. This eliminates the possibility of microstrip, both as an antenna and a transmission line. Dipoles were then examined as an alternative.

### 4.1.2 Dipoles

A dipole antenna is one of the most basic antenna types available. It consists of a straight wire, typically a half wavelength long, which is open at the midpoint and fed by a balanced two-wire transmission line, as seen in Fig. 9.

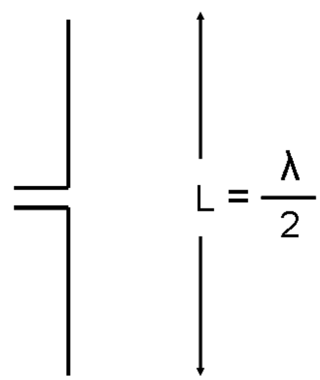


**Figure 9—**A half-wavelength center fed dipole antenna

In practice, the dipole must be cut slightly shorter than a half wavelength to achieve resonance (the point at which the reactive part of the input impedance is zero), due to end effects which make the effective electrical length slightly longer than the physical length. At resonance ($L \approx .485\lambda$), the half-wavelength dipole has an all-real input impedance of approximately 73 Ω, which is well-suited for impedance matching [20].

The half-wavelength dipole appeared to be a better choice than the microstrip patch for the roadbed antenna design for several reasons: it is a planar design, it has a planar feed structure (two parallel wires or flat conductors), it is easier to construct and impedance match, and it has a desirable radiation pattern (which is discussed in detail later). However, even though it is preferred that the antennas be woven into the geotextile, it is possible to create the transmission capable roadbed by either woven or nonwoven means. To accommodate both options, it was determined that both planar and nonplanar structures should be examined. Both dipole and patch antennas were then constructed and tested, with preference given to the dipole for the woven transmission capable roadbed design.

## 4.2 Construction Procedure

Because there were different types of antenna designs to be tested, it was desired that they be constructed with easy-to-use materials and simple tools. The roadbed fabric, which was used as a dielectric substrate, was made of woven polypropylene. For the conducting antenna elements, copper tape was used, which allowed several patch and dipole designs to be constructed with ease, using just scissors to form the necessary geometries. It has been shown that copper tape can be a good approximation of woven copper fabric [17].

After creating the appropriate antenna shape, an SMA launcher was soldered to the antenna feed point to provide a good electrical connection when testing. For the dipole antenna, a balun was soldered between the antenna feed point and the SMA launcher. This was done to ensure that the current was properly distributed along the antenna. Examples of the various dipole and patch assemblies that were constructed and tested are shown in Fig. 10.

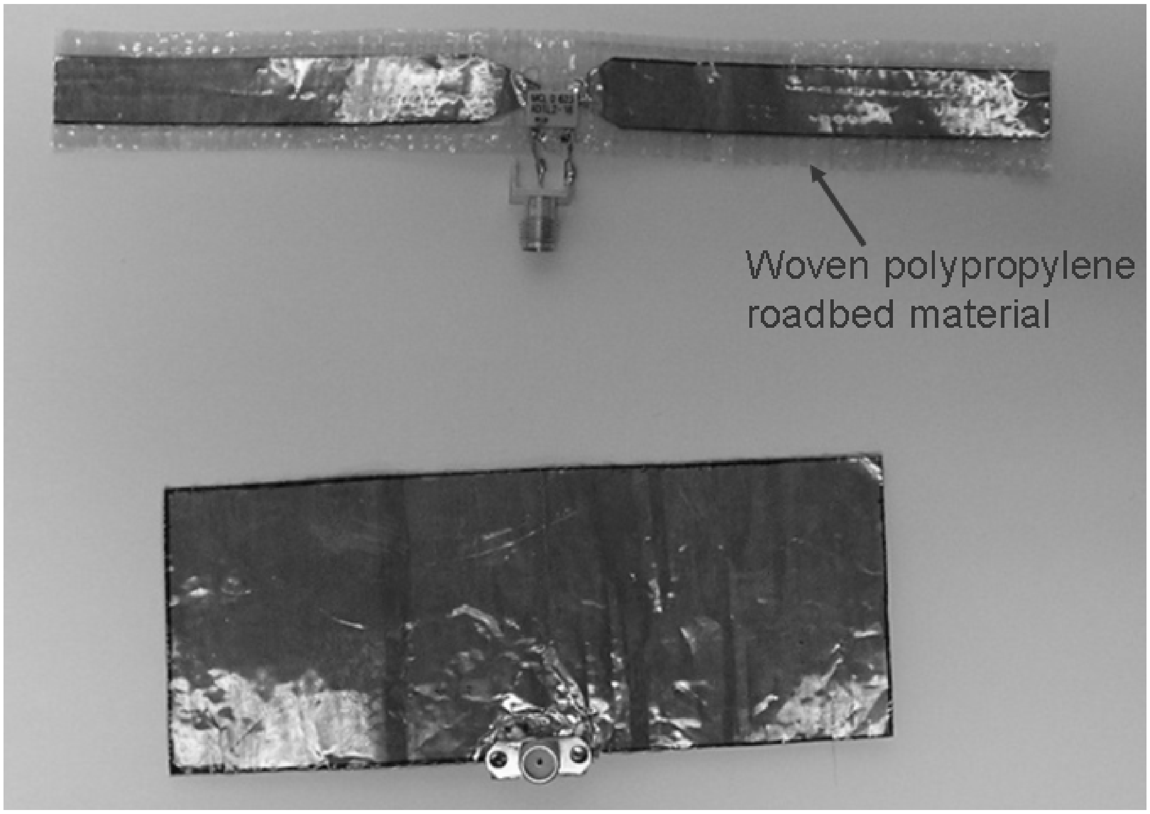


**Figure 10—**Fabric dipole (top) and patch (bottom) antennas

### 4.3 Antenna Measurements

After constructing the roadbed antennas, measurements were taken to determine their functionality. When testing antennas, two of the main concerns are how efficiently it radiates and its radiation pattern (the direction of maximum and minimum radiation). To answer these questions, the VSWR and radiation pattern of each antenna were measured. The results were then compared to known values of conventional antennas.

#### 4.3.1 VSWR

The VSWR is given by

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

where Γ is the antenna's reflection coefficient. The reflection coefficient varies from -1 to +1, and 0 indicates no reflection while $\pm 1$ indicates total reflection. When the antenna is perfectly matched, all of the supplied power will be absorbed by the antenna and none will be reflected (Γ = 0 and VSWR = 1). If the antenna is efficient most of the absorbed power will be radiated. Conversely, a poorly designed antenna will reflect most of the input power and consequently radiate very little power ($|\Gamma| = 1$ and VSWR = ∞). Since the reflection coefficient is frequency dependent, the VSWR is useful in determining how well an antenna is matched over a range of frequencies.

The VSWR is measured using a vector network analyzer (VNA), which directly measures the reflection coefficient and then calculates the VSWR. The antenna is first connected to one of the VNA's ports. The VNA supplies a small amount of power and measures the power level reflected back into the port. The ratio of reflected power to supplied power is used to find the reflection coefficient, which is then used to calculate the VSWR.

As discussed, a well matched antenna will have a VSWR near 1. The VSWR for the 2.8 GHz patch antenna, measured over the frequency range from 2 GHz to 3 GHz, is shown in Fig. 11.

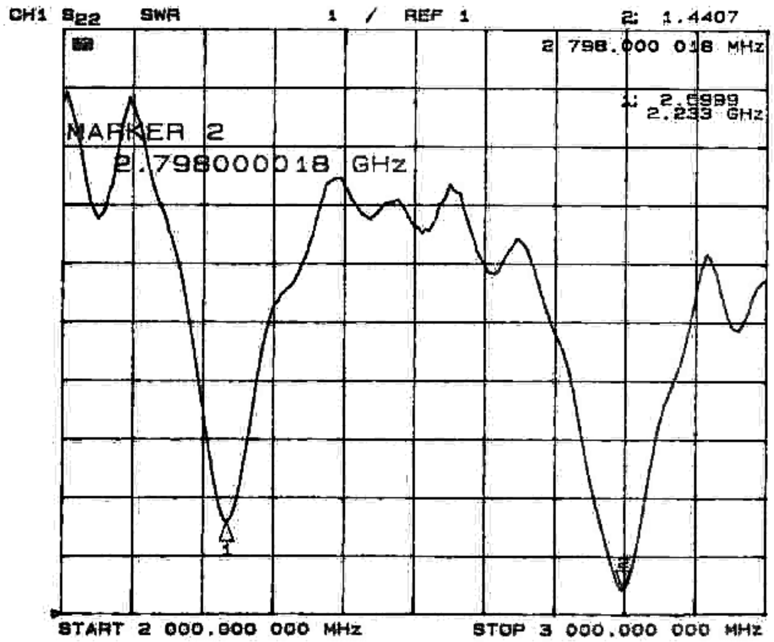


**Figure 11—**Measured VSWR of the 2.8 GHz patch antenna

It can be seen that a minimum occurs at 2.798 GHz, giving a value of 1.44 as indicated by marker 2. This shows that the antenna is well matched and therefore a good radiator at this frequency.

### 4.3.2 Radiation Pattern

The radiation pattern is a measure how well an antenna radiates in each direction, and is defined by the physical geometry of the antenna (for instance, an isotropic antenna is a theoretical device that radiates equally in all directions. Its radiation pattern in any plane would therefore be a circle since it transmits, and therefore receives, equally well in all directions). It is often measured by rotating an antenna in a plane and measuring the received signal as it turns.

The radiation patterns of the fabric antennas that were constructed were measured using the Desktop Antenna Measurement System (DAMS) seen in Fig. 12.

**Figure 12—**Pattern measurement equipment, left: transmitting antenna and receiving antenna connected to turntable in anechoic chamber, right: DC power supply, platform controller, digital multimeter, and computer, not shown: power amplifier and RF detector

The DAMS is comprised of a turntable (to rotate the test antenna), a platform controller (which rotates the turntable as dictated by the software), and software that reads and records the values from the measurement device in addition to commanding the platform controller. Additionally, we use a power amplifier, an RF detector, a DC power supply, a voltmeter, and a vector network analyzer (VNA) in conjunction with the DAMS. To measure a radiation pattern, a wave is emitted from the transmitting antenna hooked up to the VNA (acting as the source). The test (receiving) antenna is rotated $360^o$ as the platform controller turns the turntable. The power received is then amplified by the amplifier and converted to a DC voltage by the RF detector. This voltage is measured every $10^o$ by the voltmeter and recorded and graphed by the DAMS software.

In order to get a full picture of an antenna's radiation pattern, both its electric (E plane) and magnetic (H plane) field radiation must be examined. This is done individually by properly orienting the transmitting and receiving antennas. The electric and magnetic field lines for a dipole are shown in Fig. 13.

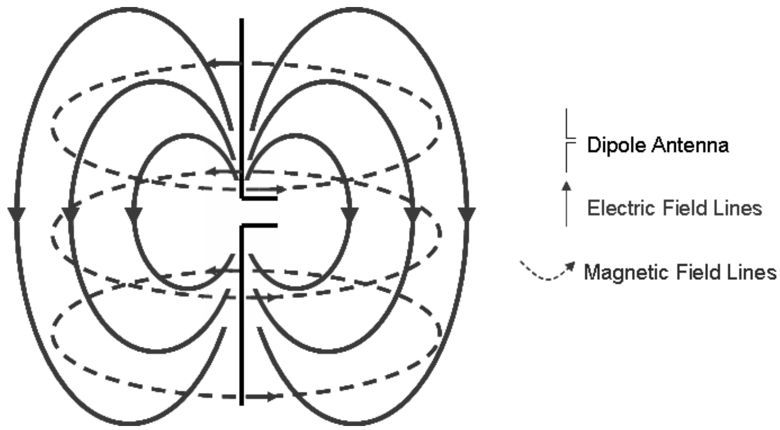


**Figure 13—**Electric and magnetic field lines for a dipole antenna

To measure the magnetic field radiation pattern, the antenna is mounted vertically on the rotating platform so that it rotates about the E plane axis. In this configuration the electric field stays constant and only the magnetic field changes as the antenna is rotated. Conversely, to measure the electric field, the antenna is mounted horizontally on the rotating platform so that it rotates about the H plane axis. In this configuration the magnetic field stays constant and only the electric field changes as the antenna is rotated. To achieve maximum polarization alignment in each case, the transmitting antenna must be oriented in the same way as the receiving antenna (i.e. when measuring the magnetic field, the transmitting antenna must be vertical, when measuring the electric field, it should be horizontal).

Since the radiation pattern is defined by the geometry of the antenna and since the test antennas have known geometries, their theoretical patterns are known. However, when the fabric patch antenna was first measured, the results looked nothing like the expected theoretical results. It was then necessary to assess the accuracy of the pattern measurement equipment.

After taking apart the system and testing each component, it was determined that the RF detector was the cause of the error. Initially it was assumed that the detector had a linear response over its entire range of input voltages. Fig. 14 shows the measured response curve of the detector, indicating a nonlinear region from -50 to -25 dBm and a linear region from -25 to -10 dBm. (Note: the measurements were taken with the amplifier—which has a gain of 24 dB—connected to the input of the detector in order to characterize the system more thoroughly. Hence, the actual input power into the detector was 24 dB greater than the previously given values, which were the input values at the amplifier. The detector alone then has a nonlinear range from -26 to -1 dBm and a linear range from -1 to +14 dBm, whereas the total system, with the amplifier at the detector's input, follows the originally stated trend).

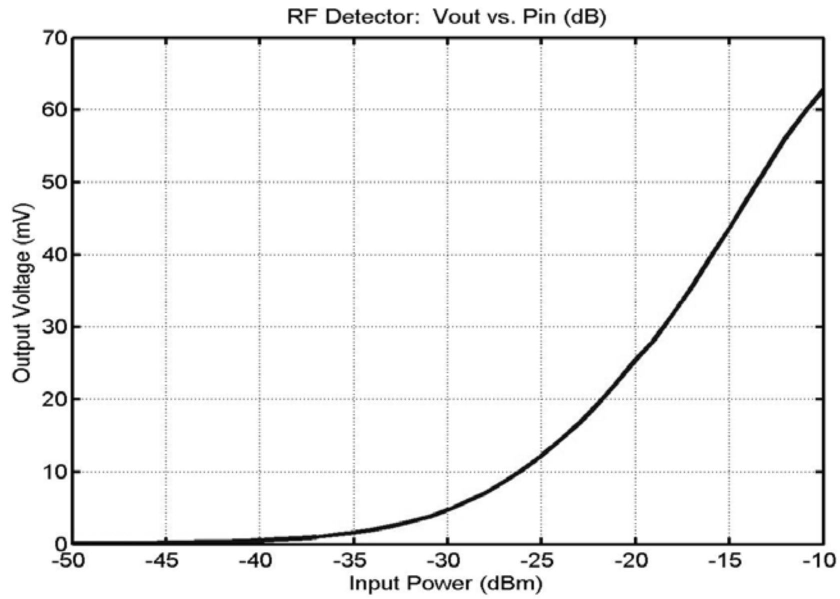


**Figure 14—**System characteristics with amplifier connected to RF detector: output voltage (mV) vs. input power (dBm)

Steps were then taken to fix the error caused by the detector's nonlinearity. Alterations in the pattern measurement setup were made so that the detector would be operating mostly in its linear range. Also, a code was written in Matlab to extract the real power values from the exported data to generate an accurate radiation pattern. Once this error was accounted for, the measured data closely resembled the theoretical patterns that were expected, as seen for the dipole in Fig. 15.

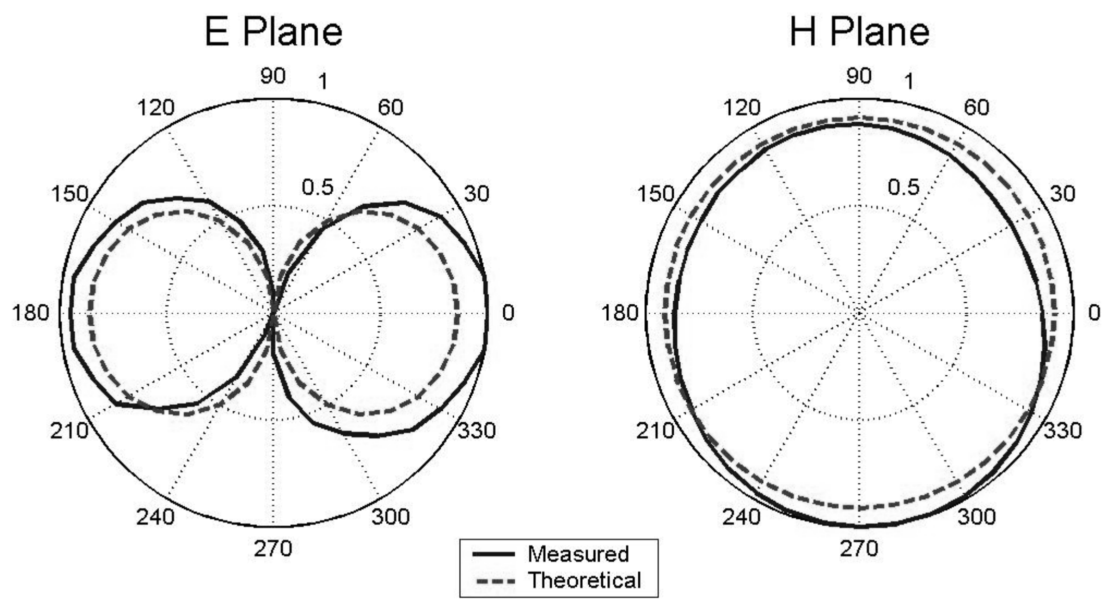


**Figure 15—**Measured and theoretical patterns for the 900 MHz fabric dipole

The importance of the radiation pattern in the design of the transmission capable roadbed cannot be overstated. Since the proposed WLAN should communicate effectively along the road, it is imperative that the antennas radiate well in that direction. However, it might be advantageous for the antennas not to radiate well toward the side of the road, which could reduce outside interference. The radiation pattern of the dipole is well suited for this purpose, since as indicated by Fig. 16 its main lobes and nulls are in perpendicular directions.

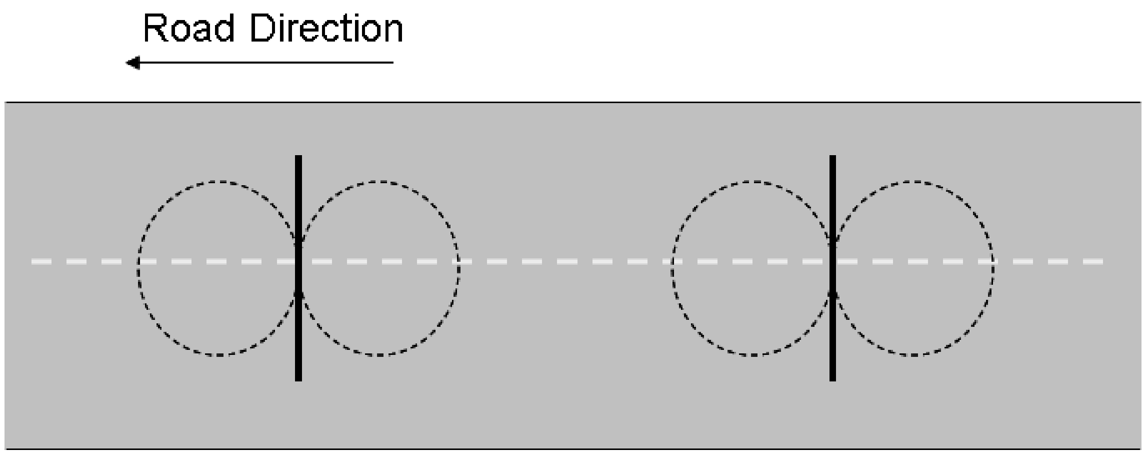


**Figure 16—**The radiation patterns of dipoles laid perpendicular to the direction of the road will radiate along the road but not off it

The data from the VSWR and radiation pattern measurements showed conclusively that antennas could be built using geotextile roadbed fabric as a major component without any significant deteriorating effects. In each test, the fabric antenna performed as well as conventional antennas of similar design. It was therefore apparent that antennas could be built into geotextile roadbeds and buried under asphalt and still transmit above ground. In short, proof of concept was achieved. However, several other specific system questions still needed to be addressed.

# CHAPTER 5

# FEED STRUCTURE

The first great design challenge after showing proof of concept was determining how to get the signal power from the side of the road to the antenna. Traditional means such as coaxial cable might be bulky and impractical. Instead of using coax we decided to investigate a form of transmission line that could be incorporated into the geotextile roadbed. In order to be mounted onto the roadbed without altering its shape or compromising its structural integrity required that the transmission line also be woven into the roadbed. Since roadbeds are planar surfaces and the copper conductors are meant to be woven into this planar surface, the transmission line would also have to be planar. This meant that microstrip (which would otherwise be a relatively simple solution) would not be possible, since it requires multiple copper layers. Two possible planar transmission line designs were examined: twin-lead, and coplanar waveguide.

## 5.1 Twin-lead

Twin-lead is a transmission line configuration consisting of two parallel conductors, as in Fig. 17. Its characteristic impedance is set by the ratio of the conductors' diameter, d, and the space, s, between conductor midpoints.

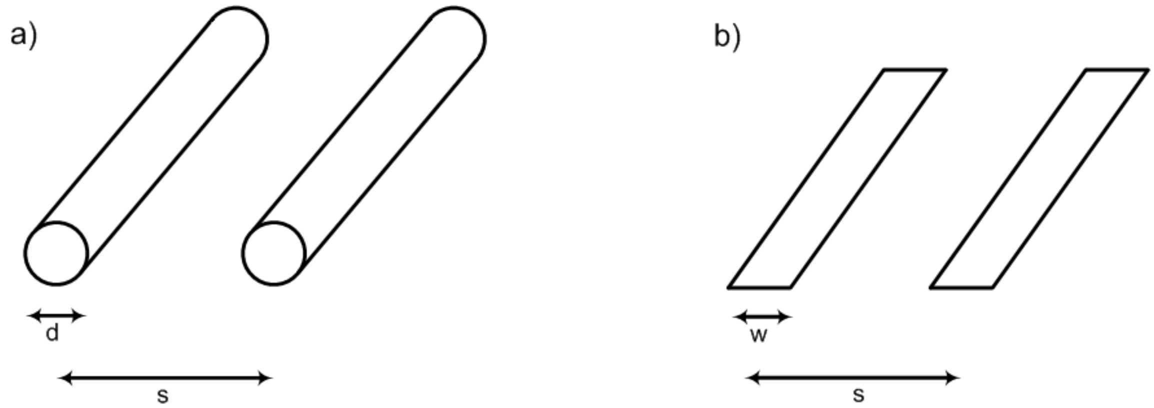


**Figure 17**—Twin-lead examples for a) round wire, and b) flat conductors

Twin-lead became popular as a balanced feed for television antennas. It was commonly made into 300 Ω ribbon cable, which matched well with a 75 Ω antenna using a 4:1 balun [22]. For the geotextile roadbed feed structure, twin lead seemed to be ideal. It is a planar configuration and if it could be designed to be 75 Ω (by properly adjusting the width and spacing of the conductors), there would be no need for a balun as both the dipole and twin-lead are balanced structures.

Unfortunately, further investigation revealed that twin-lead would not be a possible feed structure design for the roadbed antennas. The characteristic impedance of a length of twin-lead is calculated as

$$Z_c = 120 \ln (2s/d)$$

Since the two conductors have a minimum separation of d without overlapping, as demonstrated in Fig. 18, a minimum threshold for the characteristic impedance can be found.

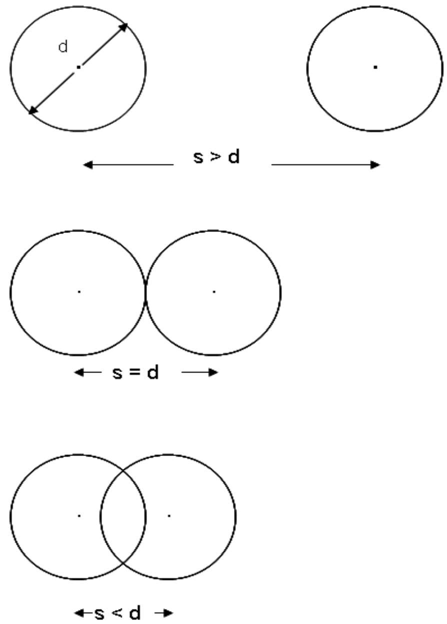


**Figure 18—**Overlapping of the conductors occurs if the separation is less than the wire diameter

By setting the separation to its minimum (s = d), the minimum characteristic impedance that can be realized is about 83 Ω. However, even this 83 Ω characteristic impedance would be impossible to implement as the two conductors would be touching. Some additional separation would be required to construct a practical design, which would further increase the characteristic impedance. Additionally, in order to use twin-lead to feed the roadbed antennas, the two conductors would have to be flat and on the same plane, as in Fig. 19.

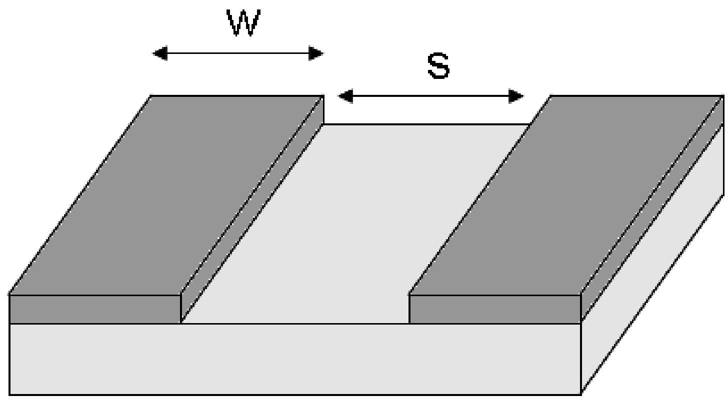


**Figure 19**—Coplanar strip geometry

To achieve the same 83 Ω impedance using coplanar strips, the conductor width, w, would have to be 50 times the spacing, s, between them (and even greater for a lower impedance) [23]. Even with spacing as small as a half inch, the strips would have to be over 2 ft. wide! This would be highly sensitive to slight deviations in spacing and completely impractical to implement. Because of the difficulties in producing an acceptable twin-lead feed structure, coplanar waveguide was examined as a possible solution.

## 5.2 Coplanar Waveguide

Coplanar waveguide, or CPW, is a transmission line configuration in which a signal line conductor runs between two ground planes on the same surface on top of a dielectric substrate, as shown in Fig. 20.

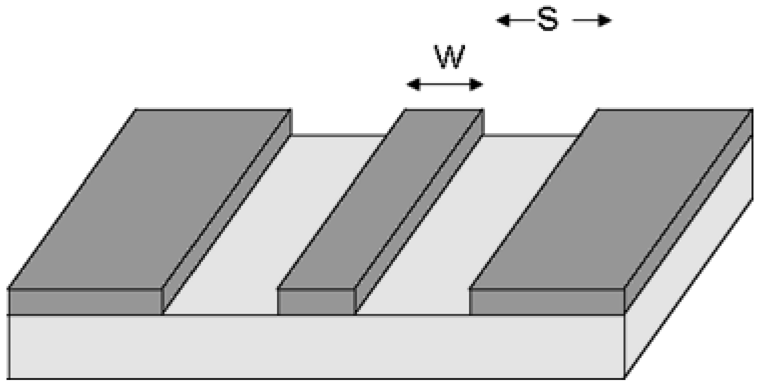


**Figure 20—**Coplanar waveguide geometry

The characteristic impedance of CPW is set by the ratio of the signal line width, w, to the spacing between conductors, s. Hence there are an infinite number of possible ways to design a 50 Ω CPW line by adjusting the width and spacing to the correct ratio. There is a tradeoff with reducing the size, however, as skinny lines are more lossy.

It was desirable to construct a 50 Ω CPW line made from the same materials as the fabric roadbed antennas. This would enable the construction of an entirely self contained system built into the roadbed and requiring only external power. The initial calculations of the line width and spacing were performed with the Linecalc tool in Agilent's Advanced Design System (ADS) [24]. A reasonable solution was found with a signal line width of 125 mils and gap spacing of 250 mils, resulting in a 54 Ω line. The design was constructed using similar methods as in the fabrication of the fabric antennas and then tested.

### 5.2.1 Time Domain Reflectometry

The impedance of the CPW line was measured using time domain reflectometry (TDR). This technique measures the reflection coefficient, Γ, in the time domain as a short pulse is sent through a section of transmission line. From the measured Γ, the characteristic impedance can be calculated. If everything is matched, the TDR output will be constant at zero, but at mismatch boundaries the output will jump as some of the signal will be reflected. Because the output is shown versus time, and the pulse travels at a relatively constant speed, the results can be viewed as a graph of the reflection coefficient as a function of position on the line. A graphical representation of the test CPW line is shown in Fig. 21.

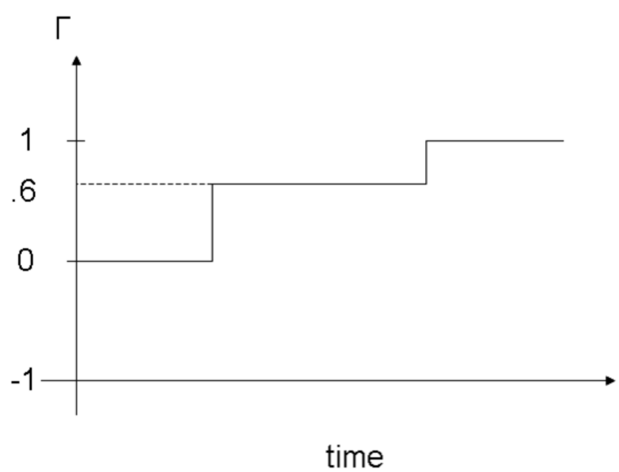


**Figure 21—**Reflection coefficient as a function of time for the CPW line using TDR

The reflection coefficient remained at 0 while the pulse traveled along the network analyzer's 50 Ω test cable, but jumped up to a value of .6 when the pulse reached the CPW line. It then remained at .6 until the line was terminated in a short circuit, at which point the reflection coefficient jumped up to 1. From this measurement, the VSWR of the line was determined to be 4, and the characteristic impedance of the CPW line was therefore 200 Ω.

### 5.2.2 Estimation Errors

This value was a surprise as the intended impedance was 50 Ω. The discrepancy comes as a result of several assumptions made when performing the initial calculations. Because of the small scale and lack of precision measuring equipment, the dielectric thicknesses was estimated. Also, the effective dielectric constant, $\varepsilon_{eff}$, was estimated. Typically for CPW, the $\varepsilon_{eff}$ is approximately equal to the average of the dielectric constant of the substrate material and that of air. This result is a consequence of half of the fields being confined within the substrate and half in air [25]. This approximation is based on the assumption that the substrate is sufficiently large (ideally infinite) so as to attenuate the fields within it so they do not escape through the bottom. Because the thickness of the substrate is limited to the geotextile roadbed thickness, this condition could not be met. Consequently, a significantly greater amount of the EM fields were in air than in the dielectric. This disproportionate amount of fields in the lesser dielectric (air) was believed to reduce the effective dielectric constant.

Furthermore, the relative permittivity, $\varepsilon_r$, was believed to be lower than the number often cited for solid polypropylene, 2.2. This is because the material used in the construction of the CPW line is a woven polypropylene, which is believed to have a lower dielectric constant than a solid slab of polypropylene. So, if the substrate had a dielectric constant of 2.2 and was sufficiently thick, the effective dielectric constant for the CPW line would then be the average of 2.2 and 1, which equals 1.6. Yet because the estimations stated seemed to reduce the effective dielectric constant, it was estimated to be approximately 1.

### 5.3 System Matching with Baluns

Even with a characteristic impedance of 200 Ω, the constructed CPW line is still usable for the transmission capable roadbed design. The line would require a 4:1 balun at each of its ends to match it to a 50 Ω system. Fig. 22 shows the complete transmission capable roadbed, including baluns for impedance matching.

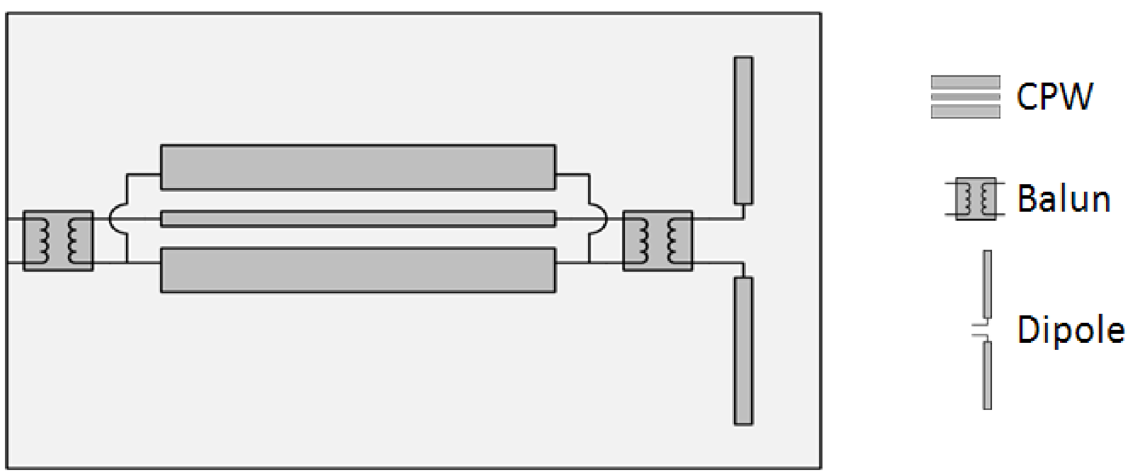


**Figure 22—**The total transmission capable roadbed design

A balun is a device used to match unbalanced structures, like coaxial cable and CPW, to balanced ones, like twin-lead and dipoles, usually by means of electromagnetic coupling (often a transformer). The use of a balun between the CPW and the dipole antenna of the transmission capable roadbed design is therefore necessary to maintain compatibility within the system. Without a balun in place, the current distribution along the dipole would be uneven, which would distort the radiation pattern.

Another useful feature of baluns is their impedance matching capabilities. By adjusting the turns ratio of a transformer balun, an impedance conversion is made from one side of the device to the other. This can be quite useful, especially for impedance matching balanced antennas to unbalanced feeds as in the case of the roadbed system.

# CHAPTER 6

# CONCLUSIONS AND FUTURE WORK

With a possible feed network design in place, all of the major components of the transmission capable roadbed have been modeled and tested. It was shown that antennas could transmit through a typical road-sized thickness of asphalt, antennas were constructed using geotextile roadbed fabric as a major component, a potential feed structure was successfully built, and the system impedance matching concerns were addressed. The successful completion of this modeling phase brings about the next step in the project to work towards a finished prototype.

The first course of action will be to begin testing woven structures—both for the antennas and the feed structure—and comparing them to the copper tape designs from the modeling phase. This will be a very involved process, in which significant knowledge will be gained. A novel approach to weaving the appropriate geometrical patterns of copper thread into the geotextile roadbed fabric will be required. The comparison of the woven structures and the copper tape assemblies will be a good indicator of how accurately the proposed system has been modeled.

After considerable testing with the woven structures, it will be time to assemble major sections of the system. Specifically, the antenna and feed structure (with appropriate matching network) will be analyzed together and optimized. Then, multiple antenna and feed structures will be assembled on one large section of roadbed fabric to create a working prototype. This prototype will be tested in its application environment by burying it under the road. And finally, after successful testing of the prototype with laboratory equipment, the design will be completed with a power source and stand alone connections. Hopefully this work will eventually lead to the desired goal: an electronic transmission capable roadbed incorporated into the nation's infrastructure.

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