ANTENNAS

AN INTRODUCTORY GUIDE

Property of:

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ABSTRACT

This white paper is intended as a guide to understanding how antennas transmit and receive electromagnetic waves. We begin with an explanation of what an electromagnetic wave is, and how it travels. Then, by studying a half wave dipole antenna, we learn how an antenna radiates electric and magnetic fields. We discover how these radiated electric and magnetic fields travel together as electromagnetic waves. Finally, we define polarization and explain its importance in antenna design.

Table of Contents

List of Figures

Introduction

With modern electronics, antennas enable us to communicate over cities, continents, and even across the solar system. While antennas are relatively simple devices, the concepts behind them are rather complex. Our understanding of antennas will come only after understanding these preliminary topics:

- Electromagnetic (EM) waves
- Electric fields, Magnetic fields, and EM radiation
- Polarization

By studying these topics, we will be able to visualize how antennas transmit and receive electromagnetic waves.

EM Waves

EM Wave Characteristics

An electromagnetic (EM) wave consists of two separate sub-waves: an electric field wave, and a magnetic field wave. Figure 1 demonstrates their basic characteristics. The electric and magnetic field waves are mutually perpendicular, and they travel in the same direction. They also travel with the same *phase*, meaning the electric and magnetic field waves each have maximum and minimum values at the same point along the direction of travel.

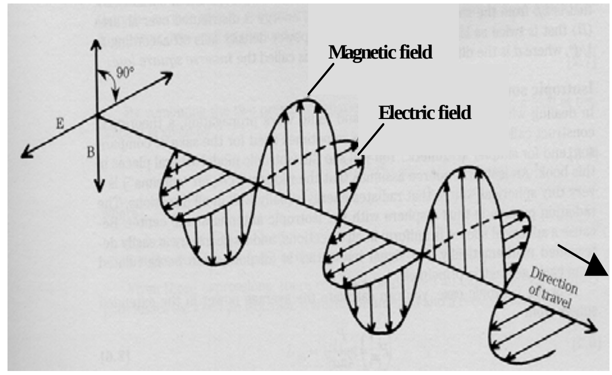

Figure 1: An EM wave consists of perpendicular electric and magnetic fields. (Adapted from the *Practical Antenna Handbook*.)

Each wave oscillates about the same axis. The electric field wave is made of a series of electric field lines (shown by arrows) that grow bigger in magnitude and then smaller. Following the tips of the arrows traces out a snake-like path, called a *sinusoid*. Similarly, the magnetic field wave is made of a series of magnetic field lines, and has the same sinusoidal shape.

EM Wave Propagation

One interesting characteristic about EM waves is that the direction of wave *propagation*, or travel, is always perpendicular to both the electric field and the magnetic field. The electric field, magnetic field, and direction of travel for an EM wave follow what is known as the *right hand rule*, explained in Figure 2.

The Right Hand Rule

Put your right hand out like you are going to shake someone's hand, with your fingers pointing directly forward and your thumb pointing straight up. The direction of your fingers represents the positive direction of the electric field. The direction of your thumb represents the direction of travel. Which way is the direction of the magnetic field? Simply curl your fingers 90 degrees to the left, and that is the positive direction of the magnetic field.

Figure 2: The right hand rule relates the electric field, magnetic field, and direction of travel.

By understanding the right hand rule, one can always know the orientation of the electric field, magnetic field, or direction of travel, as long as two out of the three are known.

EM waves can be further understood if one knows three general wave characteristics: *wavelength*, *frequency*, and *velocity*. These characteristics are reviewed in Figure 3.

Wavelength (λ) – the distance between successive positive peaks (given in meters).

Frequency (f) – the number of wavelengths per unit of time (given in Hz, which is 1/second).

Velocity (v) – the distance a wave can travel per unit of time (given in meters/second).

Figure 3: Wave characteristics; wavelength, frequency, and velocity defined.

Wavelength, frequency, and velocity are related by the following equation:

$$\lambda \cdot f = v .$$

The wavelength and frequency are characteristics that are specific to a wave, while velocity is specific to the medium through which a wave travels (Ulaby 16).

The velocity changes according to the medium in which a wave is traveling. For example, a wave travels through air (an approximate vacuum), or *free space*, at ~300,000,000 m/s. This velocity is known as the constant "*c*," or the speed of light. It is the fastest velocity at which an EM wave can travel. This velocity applies to every waves traveling through free space, regardless of what wavelength or frequency it may be.

We have just learned many of the basic properties of EM waves, including their behavior while traveling. We are now ready to see how EM waves are produced by antennas.

ELECTRIC FIELDS, MAGNETIC FIELDS, AND EM RADIATION

ELECTRIC FIELDS

The basic functionality of an antenna is that a voltage is applied, which causes a current. The voltage produces an electric field, and the current produces a magnetic field. These fields radiate away from the antenna as an EM wave, in the manner shown back in Figure 1.

Before getting into a discussion on EM fields, it is important to know the difference between D.C. and A.C. voltage. D.C. (direct current) voltage is a constant level of voltage. For example, a 3-Volt battery is D.C., because it supplies a constant 3 Volts over a period of time.

A.C. (alternating current) voltage, on the other hand, is always changing. It looks like a sinusoid (like the two perpendicular sinusoids shown in Figure 1). A.C. voltage ranges from one voltage to the negative of that voltage. For example, a 3-Volt A.C. voltage source would have a value of 3 Volts at only one point in time, per cycle. It would then decrease sinusoidally past 0 Volts down to a value of –3 Volts, whereupon it would increase again up to 3 Volts, and repeat the cycle.

Now back to EM radiation. The easiest way to understand how an antenna radiates EM waves is by modeling an antenna as a *capacitor*. A capacitor is a device that can store a charge between two conductive plates.

A typical parallel-plate capacitor is shown in Figure 4(a), where it is connected to a D.C. voltage supply (represented by an E inside of a circle). A voltage applied to two plates produces an electric field between the plates (Carr 125). The electric field lines are shown by arrows pointing from the positively charged plate (+) to the negatively charged plate (–).

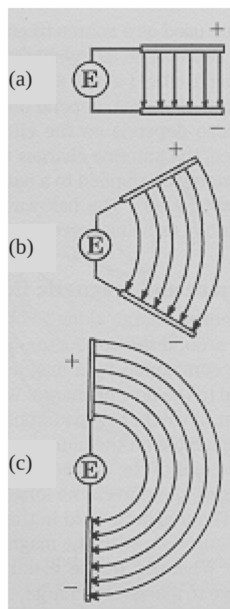

Figure 4: Voltage applied to a capacitor produces an electric field between the capacitor's plates. (Courtesy of the *Practical Antenna Handbook*.)

Figures 4(b) and 4(c) show the change in electric field lines due to a change in the orientation of the capacitor's plates. Note that the electric field lines *always* hit the conductive plates at right angles from the plane of the plate. This is due to *boundary conditions*, which is an advanced topic for the scope of this paper. All you need to know about boundary conditions for our discussion is that an electric field can only be next to a conductor if it is at a right angle from the plane of the conductor (Pozar 15). The importance of this phenomenon will shortly be seen.

Our discussion on capacitors has prepared us for our first antenna: the half wave (“1/2 λ,” or λ/2) dipole. The λ/2 dipole antenna is very similar to the capacitor of Figure 4(c). Shown in Figure 5, the λ/2 dipole has two conductive elements that point in opposite directions.

The antenna is *fed*, or supplied with voltage, by the two wires connected to the middle of the antenna. Figure 5(a) shows a voltage being applied (note the + and – signs), which creates an electric field (shown by the lines with arrows). So far this looks like the model in Figure 4(c).

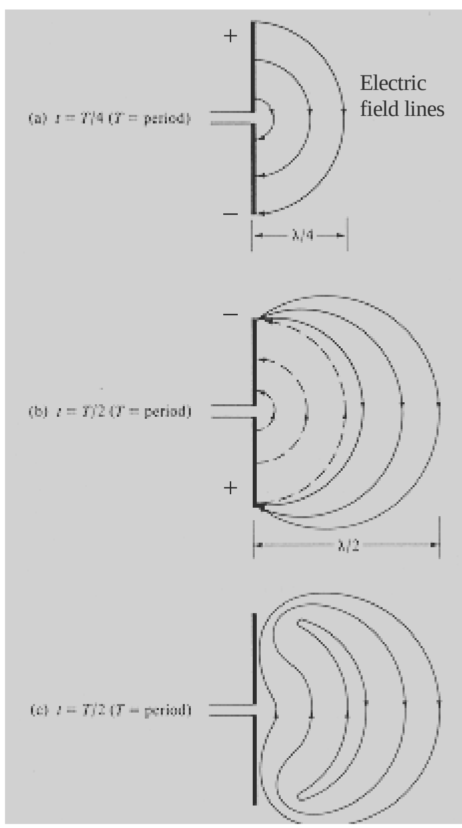

Figure 5: An electric field is formed from a short dipole. (Courtesy of *Antenna Theory*.)

We are applying A.C. voltage, though—not D.C. This means that after an amount of time, the voltage changes from the top conductor being positive and the bottom negative, to the bottom conductor being positive and the top negative (see Figure 5(b)). Note the consequential change in the direction of the electric field lines. As this sequence of alternating voltages continues, an alternating electric field *loop* “detaches” from the antenna, and radiates outward. Figure 5(c) helps to visualize how these electric fields loops radiate from the antenna, and propagate outward into the surrounding medium.

Recall our brief discussion on boundary conditions. Because the antenna is made of conductive material, the electric fields only touch the antenna elements at right angles. This fact is what makes the electric fields detach in loops. The loop shape makes it possible for alternating electric fields to propagate through a medium.

As these electric fields propagate, they spread out, as shown in Figure 6. Note that the direction of propagation is not just perpendicular to the antenna, as one might expect. The top of the electric field loops travel slightly upward, and the bottom of the loops travel slightly downward. The overall effect is a spherical-like radiation pattern.

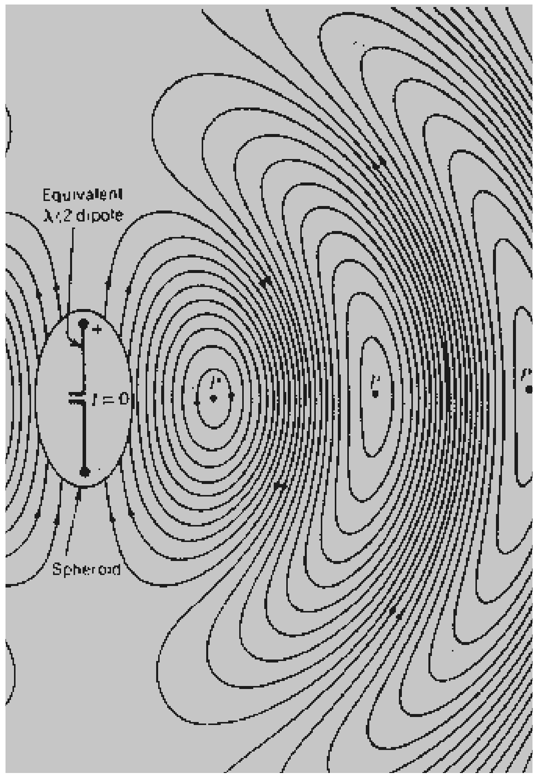

Figure 6: Electric fields spread out as they propagate from an antenna. (Courtesy of *Antenna Theory*.)

This spherical-like radiation is important if you are interested in the radiated field very close to the antenna, known as the *near field*. In most cases, however, the region of interest is sufficiently far away from the antenna, so that it is assumed that the direction of propagation of the electric field lines are completely perpendicular to the antenna. This is a result of the *far-field* approximation (Kong 510).

Let us validate this approximation using Figure 6 and some intuition. Find a measuring device (your finger will do fine), and hold it up to the λ/2 dipole antenna at the left of the picture. Measure the length of the antenna, and then hold that same length in front of the electric field lines at the far right of the picture. (Move straight to the right, without rotating or moving up or down.) Notice how much more vertical the electric field lines are than at the left near the antenna.

For the length of the antenna, especially, in this region, the electric field lines are very close to being vertical. The distance (r) from the antenna where the far-field approximation is accepted is defined as:

$$r > \frac{2 \cdot D^2}{\lambda},$$

where D is the diameter of the antenna, and λ is the wavelength of the EM signal being transmitted or received.

This is the basic idea of how the far-field approximation works. This approximation is significant because it greatly simplifies the math for solving field radiation problems. For communication engineering involving antennas, the far-field approximation plays a vital role. All explanations of antennas in this paper will assume that the receiving antenna is in the far-field region.

You have just learned how a typical antenna radiates electric fields. All it took was some practice working with capacitors, A.C. voltage, boundary conditions, and radiation fields. Once we learn about magnetic fields, we can combine it with our knowledge of electric fields to understand EM radiation.

MAGNETIC FIELDS

Earlier in the paper we discussed the Right Hand Rule. The Right Hand Rule helped us to visualize how magnetic fields are perpendicular to electric fields, and how they are both perpendicular to the direction of travel (review Figures 1 and 2). This gives us some intuition for understanding how antennas radiate magnetic fields.

First of all, we must understand that electrical current through a wire produces a magnetic field around it. The direction of the produced magnetic field is a clockwise or counter-clockwise circle, centered on the direction of current flow (see Figure 7).

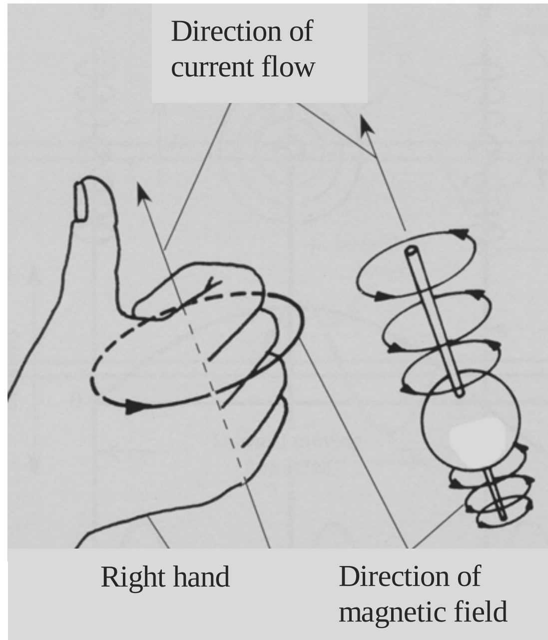

Figure 7: Current through a wire produces magnetic fields. (Adapted from the *Practical Antenna Handbook*.)

In general, we can follow the Right Hand Rule (explained in Figure 2) to know the direction of the magnetic field. Simply point your thumb in the direction of the current, and then curl your fingers. The rough circles indicated by your curled fingers represent the magnetic field encircling the current. Your fingertips point in the direction of the magnetic field lines.

Now pretend that the direction of current flow is in the opposite direction. Point your thumb in the direction of current flow and curl your fingers. You will notice that the magnetic field lines are now pointing in the opposite direction.

You can imagine that when an A.C. voltage is supplied to the wire, or antenna, the direction of current flow alternates, and as a result, the direction of the magnetic field lines alternates, as well. This results in a radiated magnetic field that travels outward and perpendicular to the antenna.

This radiated magnetic field oscillates in magnitude as a sinusoid, due to the change in magnitude and direction of the magnetic field lines. In the far-field, these lines look similar to the electric field lines of Figure 6.

Following what you learned from Figure 7, imagine the magnetic field lines produced by the antenna in Figure 6. They have the same spacing between lines as the electric field, and they touch the axis of the direction of travel (which points from left to right) at the same points. The main difference is that the electric field lines are pointing up and down in Figure 6, and the magnetic field lines are pointing out of the page and into the page.

With our knowledge of magnetic fields, we are ready to put the electric and magnetic fields together for EM radiation.

EM Radiation

To see the magnetic field and the electric field traveling together, first look at Figure 1, and imagine a dipole antenna in place of the E axis. Exaggerate the heights of the electric field lines, and you will see a picture similar to Figure 6. Take note of when the direction of electric field lines change.

Similarly, exaggerate the heights of the magnetic field lines, and you can see the magnetic field in the far-field. Putting the electric and magnetic fields together, you can picture EM radiation in the far-field.

In summary, an A.C. voltage source connected to an antenna produces alternating voltage and current. This produces, respectively, alternating electric and magnetic fields. These fields travel together, as radiated EM waves, outward from the antenna.

Polarization

Definition of Polarization

Now that we understand how basic antennas radiate EM fields, we can learn the great importance of *polarization*.

Polarization is one of the key concepts to understanding the shape of antennas.

First, we must understand the two primary ways in which polarization can be defined. It can either be used in describing an antenna or a radiated wave. Figure 8 gives us a simplified definition for each of these two uses:

Polarization of an antenna – the same as the polarization of the wave radiated by the antenna.
Polarization of a radiated wave – the direction of the electric field of a radiated EM wave, over time (Carr 12).

Figure 8: Polarization is defined as either describing an antenna or a radiated wave.

Polarization is best understood with examples. We will learn about the most widely used polarization: linear polarization.

LINEAR POLARIZATION

A linearly polarized antenna produces a linearly polarized EM wave. The dipole antenna (λ/2, or any other length) is a good example for linear polarization.

The radiation pattern of a dipole antenna was shown in Figure 6. You will recall that the electric field lines in the far-field pointed in only two directions: either up or down. This demonstrates that the EM waves radiated by the dipole antenna are *linearly polarized*. More specifically, because the lines only point up or down, we have *vertical polarization*.

Now picture the same antenna rotated 90 degrees (so that it is now horizontal). The electric field lines radiated by the antenna would still be linearly polarized. However, the lines would point left or right. The EM waves radiated by the horizontal dipole antenna are *horizontally polarized*.

In general, you can know if an EM wave is linearly polarized if you will first put your finger on a certain point in space in the far-field of an antenna. Then picture the electric field lines that cross that point as time goes by. If the electric field is always pointing in the same (or exact opposite) direction, then the wave is linearly polarized.

If a linearly polarized wave has only vertical or horizontal electric field lines, then the wave is, respectively, vertically or horizontally polarized.

Keep in mind that our discussion on polarization is simplified. Remember that the far-field approximation of Figure 6 showed that the electric field lines are only approximately linear. The polarization is only approximately linear, as well.

Our knowledge of polarization will enable us to understand its importance. This discussion follows.

Importance of Polarization

An antenna receives an EM wave in the same manner in which it transmits an EM wave. This is a direct result of the Reciprocity Theorem (Kong 706). The significance of this theorem will shortly become apparent.

Imagine an EM wave traveling toward a dipole antenna. How should this antenna be oriented so that you get the best reception? Should you point it vertically? horizontally? straight at the wave like in a joust? The answer is: it depends on the polarization of the EM wave.

Consider a vertically polarized EM wave, for example. **Just as the vertical dipole of Figure 6 radiated vertically polarized EM waves, a vertically polarized EM wave needs a vertical antenna to receive it.** This is because—if you recall from previous discussions—a vertically polarized EM wave has an electric field that oscillates vertically. And a vertically oscillating electric field can only be transmitted, and hence received (by reciprocity), by a vertical antenna.

To be more correct, it should be mentioned that a horizontal dipole is, in fact, able to receive a vertically polarized EM wave, but just barely. This is known as *cross-polarization*, and the signal received is around 20-30 dB less than if the polarization of the antenna matched the polarization of the EM wave (Carr 13). That is, 90-97% of the power is lost due to cross-polarization.

One may conclude, therefore, that the shape and orientation of an antenna is crucial for optimum transmitting and receiving. In line-of-sight applications it is important to have a receiving antenna that has the same polarization as the EM wave that is to be received.

Conclusion

In summary, we learned what an electromagnetic wave is, and how it travels. We then saw how an antenna radiates electric fields, magnetic fields, and EM waves. Finally, we learned the importance of polarization, and its correlation with the shape of an antenna.

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