A Refresher on Antenna Properties

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I tell my students that, to me at least, antennas are amazing things. Here you have a device attached to a circuit, where voltages are present and currents flow, and from these flowing currents the antenna performs energy transformation in the form of propagating electromagnetic signals! Literally, energy leaps out into space and propagates away from the source antenna!

For as much as they are used, there are often misconceptions or mis-rememberences about them. In the course of teaching four related courses, two at the Senior undergraduate level and two at the Masters level, I finally hit on the idea of putting together a single set of lecture notes for antennas. Prior to this, I had four lectures that were sort of the same, but were tailored slightly. I realized that repetition of the basic concepts would help the student (and me as well)!

So the following is from my lecture notes for the classes I teach. I have left out a lot of the math as it does not increase the digestibility of the material. I do not claim to be an expert in the area of antennas: in fact, there are several well known amateur radio operators who are more knowledgeable than I. It is simply that I have to teach this to modern college students, a sometimes daunting task!

To kick this off, an interesting beginning concept is the idea of filters: We are familiar with electrical signal filters as such things as lowpass, bandpass, highpass, etc. We use them in everything but like most familiar things we do not *think* about their nature. Consider a bandpass filter, a very handy thing. To a first approximation, it accepts signals in the frequency domain that we want, and rejects those we do not want. This frequency domain behavior is well known, and widely used. We find that Fourier analysis allows us to describe what is happening analytically and we often use Fourier transform math to move from the time domain to the frequency domain when looking at filter problems. Indeed, the Fast Fourier Transform (FFT) is a common implementation of this math suited for computer solutions, due to its efficiency.
Let us consider now an directional antenna: it is a similar device in that it accepts signals from a given region of space and rejects those from other directions. In this regard, it has a behavior similar to a bandpass frequency filter, except it is doing it in the spatial domain: It is a "**spatial**" filter. As such, it turns out that the Fourier transform can be used to describe the fields from the antenna in both the near field region (Fresnel) and the far field region (Fraunhopfer). You can transform near-field solutions into their far-field representations and FFT routines have been written to do this. This is the basis for the so-called "compact" antenna range also called a near-field range. An excellent source of information on the topic is the website for the company Near-Field Systems Inc. (NSI), who recently merged with MI (the old Scientific Atlanta (SA) Antenna Range Instrumentation Group). Lots of good reading material from these two sources are now from one source. Another resource on basic antenna measurement is called "The Blue Book" by MI (SA), available as a PDF from different sources. Anyone interested in antennas ought to look this up.

The following is my notes for teaching antennas. Hopefully, the reader will find some useful information or be reminded of things already learned but not fresh at hand.

The Antenna as a Transducer: The purpose of an antenna is to act as a converter between voltages and currents flowing in circuit elements and free space propagation of electromagnetic waves. In this regard it functions as a transducer in that it converts energy from one form to another.

The Antenna as a Transmission Line Load: An antenna has a single port (generally) and connects to the circuitry through this port, in essence as a load (or line termination) for energy on the line. It can be treated using transmission line theory in this manner.

Antenna Match: Naturally, the antenna as a load on a transmission line will exhibit an impedance, which is often NOT that of the transmission line system. This will give rise to a voltage standing wave ratio (VSWR) > 1. This means that some of the energy delivered to the antenna will not be radiated, but will be reflected back to the source through the transmission line. In this general discussion, transmission line matching networks will not be discussed, this is an area of study all to itself! For our purpose, we will assume a "reasonable" match. For example, if a 2:1 VSWR is considered reasonable, then the Return loss is 10 dB (9.6) and roughly 10% of the power is reflected, 90 % available for the antenna. See efficiency.

Reciprocity: It is a feature of antennas that they are reciprocal devices: They do not care which way energy flows, into the antenna from fields and out as a current, or into the antenna as a current and out as fields. All behavior is two way! This means, in effect, the antenna receives **EXACTLY** the same way as it transmits. (Only restriction is practical in power handling capability!)

Aperture: An antenna acts as an "aperture' in free space, like a window that lets in sunlight, and the physical size of the aperture will determine how much energy the antenna can gather.

Wavelength: Wavelength, λ, is found from λ=c/f, where c is the speed of light in m/s and f is the frequency in hertz (cycles/second, dimension of 1/seconds) so the dimension is in meters. The writer has noticed the tendency of others to think that wavelength is an archaic way of expressing the band of operation. This is not so: wavelength is the link to the concept that electromagnetic waves have physical size and this is important when considering antenna dimensions and the meaning of near-field, etc. A very convenient way of expressing an antennas size is in terms of wavelength!

Aperture vs. Wavelength: It is often very convenient to express the size of the antenna in wavelengths, denoting the dimension as D so the expression $D/\lambda = D_\lambda$, Antenna size in wavelengths. We see application of this in determining gain and beamwidth of aperture antennas.

Bandwidth: The operational frequency range of an antenna, usually based on the region in the frequency domain where the antenna "looks like a good load", usually defined as where the transmission line match meets or exceeds an arbitrary number for return loss (i.e. $\leq$ 10 dB) or VSWR (i.e.$\leq$ 2:1). For simple antenna structures, a "rule of thumb" is that this is usually 10% of the center frequency would permit a reasonable match.

Point Source: A construct describing the generation of spherical waves by some source. The wavefront is curved, and the curvature is noticeable when the distance to observer is "small". **Point sources** generates spherical waves, we use a sphere as a model for power density considerations, this being a 3-D model. A familiar 2-D model is a pond, in which a stone has been dropped, the ripples being a 2-D example of a 3-D reality for antennas.

- E fields as radiated from a point source look like spherical wavefronts & have the $\frac{e^{-jkr}}{r}$ characteristic of point source, but when multiplied by $\frac{2D^2}{\lambda}$ – gives a plane wave approx.

Plane Wave: A point source at a "large" distance from the observer will have a large radius of curvature to its wavefront, such that the source wavefront will have a small phase deviation (usually taken as 1/8 λ or $\pm$11.25°) over the extent of the receiving antenna. The wavefront is still curved but the observer will not notice it as the source is "very far away" and the deviation in phase is considered small.

Isotropic Source: A purely theoretical concept that has as a property the ability to radiate (or receive) equally well from all directions (uniformly over a sphere with the isotropic source at the center). It is a useful comparison device by which all other antennas pattern properties can be modeled & compared. The closest thing in nature (no true manmade examples), is the Sun.

Poyntings Vector: Describes the power in an E-M wave as a function of the field intensities:

$S_d = \frac{1}{2} R_e\{E \times H *\}$ Basic Eq. governing power transfer in E-M wave, basically a E-M field statement of Ohms Law and power (P=E*I, or $P=E^2/R$)

Many coordinate systems can be used.

Ex. Use range (r), (el) θ & (az) δ angles: $S_r = \frac{1}{2\eta}(|E_\theta|^2 + |E_\delta|^2)$

Power density: Is expressed in Watts per square meter (W/m^2) on the surface of a sphere of radius r (in some cases may also use V/M, depending on who you are talking to!).

Directivity D (or U): The directivity of an antenna is a description of how well an antenna performs in focussing energy into a desired region of space by NOT putting energy into undesired regions of space (think candle vs. flashlight). D = Max power density from antenna/max power density from isotropic

Steradian: Is a unit of solid angle measure, it is a radian squared (~ 57.3 x 57.3 degrees) so its unit in degree measure is degrees squared. The solid angle of a sphere is 4π steradians or ~41253 degrees^2.

Antenna Efficiency η**:** Nothing in life is perfect, antennas as well. They are not 100% efficient in converting the energy delivered to them (see match discussion), implying loss of desired energy, generally into heat. The causes of losses are complex and worthy of study, but not here. Instead, we use efficiency η where $0 < \eta \leq 100\%$. Typical η will lie in a range of $55\% < \eta \leq 75\%$, or $.55 < \eta \leq .75$. A good "rule of thumb " value for η is .65 .

Gain: Gain is often the only number that interested many users. It is the directivity multiplied by the efficiency. Gain can be found in many ways. The simplest way is to measure the beamwidths of the antenna in the azimuth and elevation planes. The product of the two measurements is the solid angle of the main beam in degrees squared: $\Omega_M = BW_{Az} * BW_{El}$

Example: $BW_{Az} = 30°$, $BW_{El} = 25°$, $\Omega_M = 750$ deg^2

When the solid angle of the beam is divided into the solid anle of a sphere, the reslting number is the directivity of the antenna:

$$D\ (\text{directivity}) = 41253/750 = 55$$
$$\text{In dB } D_{dB} = 10 \log(55) = 17.4 \text{ dB}$$

True Gain involves efficiency η, let η=.65: $G = \eta * D = .65 * 55 = 33$ or 15.1 dB

We see how to calculate G if D & η are known, but often the efficiency is not known. The best way to determine gain is by a comparison of an antenna under test to a gain standard. Gain standards are often dipoles for VHF and up, and pyramidal horns in the microwave region. The reasons for these choices is that these particular types are easy to build and their performance is well known.

Boresite: The direction of maximum amplitude response from the antenna (considered where the "main beam" is pointed).

<u>Sidelobes/Backlobe</u>: Undesirable amplitude responses from an antenna, wasted energy, off axis response. This energy is part of the reason why the efficiency of an antenna is not higher!

<u>Antenna Pattern:</u> this is a directional plot is pattern of power distribution vs. angle in the far field. We use the pattern plot to define performance of antennas and form a basis of comparision. The pattern energy can be integrated (added up) and used to find the efficiency of the antenna. This procedure, called pattern integration, is no simple to implement, but is very useful as it give the efficiency directly from the pattern measurement.

Start w/ solid angle: 4π steradians in sphere = 41,253 sq. degrees

If integrating over space for antenna pattern, get all power radiated: Ω_p

Main Lobe integration: Ω_M, Side lobes & backlobe: Ω_m

$\Omega_m = \Omega_p - \Omega_M$, in steradians   Unit of integration: $d\Omega = \sin\theta d\theta d\varphi$

Efficiency of antenna: η_M in Main Beam

(hint: find this readily by using 3 dB BW in two orthogonal measures)

<u>ERP</u>: Effective (isotropic) Radiated Power: product of antenna gain times transmitter power :

$ERP=P_tG_t$

<u>Simple Beam width Approximation:</u> Beamwidth is defined typically as the angular extent in the power pattern where the amplitude drops from maximum power (boresite) to ½ of this value.

Beamwidth (BW) is an inverse function of the size of an antenna in wavelengths.
$BW= 66° \lambda/D = 66°/ D_\lambda$ The angle constant can vary from about 57 to 70 degrees and depends on the illumination function and sidelobe requirements.

<u>Near & Far Field:</u> When an antenna radiates energy in the form of electromagnetic waves, it is expected that all the power would lie in a plane at right angles (transverse) to the direction of travel (propagation). We know this from Poyntings Vector and its definition. This implies that all of the E & H fields (and the radiated power formed from their product) lie in the transverse plane. This is not so initially as the fields will exhibit some energy <u>along</u> the direction of travel, for example the E field have an $\mathbf{E_r}$ (radial) component and this will have a 1/r dependence on distance. If you are looking at the energy from an antenna in this region, you will see rapid excursions of power levels as you move away from or towards the antenna (values going up and down dramtically with small distance changes). These field values will eventually damp out (reduce in amplitude to negligible values). This distance from the antenna aperture is said to be the transition point from the near field (Fresnel) region to the far field (Fraunhopfer) region. When the distance meets or exceeds the far field limit, then the E-M fields are fully formed and exhibit no radial components. They are well behaved and the field energy will decrease as a function of $1/r^2$, showing a nice gradual decrease. As a note: there is a third region very close to the antenna, called the reactive field region. This will not be covered as it is little value to us as communicators!
How is this useful to us? It tells us when we are far enough away to make a valid measurement of an antennas true performance. How close is too close to measure antenna properly?? Consider the range R between the antenna under test (AUT) and the sensor antenna:

Reactive Field Limit: $0 \leq R < .62*\sqrt{D^3/\lambda}$ (this is near field reactive region)

Near field region - Fresnel zone or limit where $.62*\sqrt{D^3/\lambda} < R < D^2/\lambda$

Far field region- Fraunhofer zone or limit $R>>\lambda$, $R_{(ff)} = 2 D^2/\lambda$

Polarization of antennas

The polarization is taken, by convention, as the direction of E field. It can be stationary with respect to time, as in linear types (horizontal or vertical) or it can rotate as in circular polarization CP. Why would circular be desirable? Raindrops are falling in straight lines, so CP works better in the rain. How about spinning satellites vs stabilized platforms? Very handy to

Talk about polarization purity, how important this is to cross polarization ratio measurement work.

Now, an argument will be presented to illustrate that all polarization is elliptical in nature, and that the special cases we use, like vertical or right hand circular, are from this general case.

Assume a transverse electromagnetic plane wave in the far-field travelling in the X direction. Begin with two electric field vectors, E_y & E_z, no $E_{x,}$. It can be shown that these are orthogonal as any angle of a vector in the Y-Z plane projection can be resolved into two appropriate orthogonal vectors. A travelling EM wave in the far field would have no x dependence (x is direction of travel).

$E_y = A_y \sin(\omega t + \varphi_y)$
$E_z = A_z \sin(\omega t + \varphi_z)$

If $\varphi_y = \varphi_z$, then polarization is linear and direction of polarization will depend on the amplitudes, A_y & A_z.

If $\varphi_y = \varphi_z + k$, where k is a fixed constant, then polarization is elliptical (rotating) and polarization direction is time dependent and will depend on relative angular offset between φ_y & φ_z. The degree of ellipticity will depend on the amplitudes, A_y & A_z.

In the special case where $|A_y| = |A_z|$, and where $k = -90°$ ($\pi/2$), this becomes the special case of <u>circular</u> polarization.

This concept can be used to graphically picture the polarization by considering an ellipse. An ellipse has two axes, a major and a minor. If the amplitudes of the two axes represent our electric field vectors, E_y & E_z , then they can be drawn on the graph. A fixed phase relationship, $\varphi_y = \varphi_z$, creates a static picture, and the resultant vector is the vector sum of the two and will represent a linear polarization, of some fixed polarization angle. Consider the case where A_y & A_z are equal and yield a slant 45 ° resulting polarization.

The concept of rotating polarization is often difficult to visualize. Remember that the polarization is rotating at the angular frequency of the signal. For example, at 10 GHz, the rotation rate is 2π* 10 GHz = 62.8 Giga-radians/second! That E-field vector is really whipping around the circle!

If there is a phase displacement between these two vectors, the result is circular polarization if the amplitudes are equal, and elliptical if they are not. If either amplitude is 0, a linear polarization results.

Polarization Matrix: Who sees what?

Suppose you have a typical radio frequency link with a transmitting station & a receiving station. The amount of signal received will depend on several factors, one of which is the polarization "sense" between the Tx & Rx antennas. If they have the same sense, ie. both are linear vertical, then there is no degradation effect of the signal amplitude due to polarization. This case is called Co-Polarized, or Co-Pol for short. If they have to be of polarization senses that are orthogonal to one another (like vertical to horizontal, or left hand circular to right hand circular), the receive amplitude is theoretically zero! This is termed Cross-Polarized or Cross-pol. In practice, we find it is not entirely true that there is not a zero response between cross polarized antennas, as it is difficult to build antennas that exhibit perfect "polarization purity", not 100% vertical, for example. In a well designed antenna, the response to a cross-polarized signal may be 20 to 30 dB lower (1/100 to 1/1000 of the normal power response) or even greater in some special cases. However, there is some response between the linear basis set antennas and the circular basis set antennas.

Effective area of an Antenna:
The physical area (A_p) of any antenna is found from geometry and represents the area of the surface that the E-M "sees" in the plane perpendicular to the direction of propagation. The true effective area (A_e) is less, due to efficiency of the antenna η (losses, etc.).

$$\text{Effective area}: A_e = Phy\ Area * \eta$$

This affects the "gain" of the antenna:

$$\text{Gain:}\quad G = \frac{4\pi}{\lambda^2} A_e$$

For circular apertures:

$$\frac{4\pi}{\lambda^2} * \eta * \pi r^2 = \frac{\pi^2}{\lambda^2}\eta D^2 \quad \text{D is diameter of aperture}$$

A good "rule of thumb gain for dishes: $G=6.4*(D/\lambda)^2$ from $G = \eta* (\pi*D_\lambda)^2$
For rectangular apertures: $G = \frac{4\pi}{\lambda^2} A_e$,

$A_e= \eta* A*B$ A,B are dimension of rectangular aperture
$G= 4\pi* \eta* A*B/\lambda^2$

Types of antennas: There is an old joke: "There are two kinds of people in the world, those that believe there are two kinds of people in the world, and those who don't".
In the same vein, there are two kinds of antennas: E field generators & H field generators. They both will give equivalent results in far field, but may look different in near field. Examples are dipole based and current loop based. Another two types based on antenna physical construction: sheet vs. wire (Thank you John Kraus,W8JK). Examples as Yagi type array vs reflector types.

Introduce the parabolic antenna as sheet example, has very nice properties such as focusing energy to a point! One of the earliest antenna systems for microwaves, it owes it lineage to optics, and the telescope & searchlight mirror! Consider the dish as a gatherer of EM waves (think of a basket in sandstorm, an analogy I told the Arab troops I trained), the bigger the dish, the more energy gathered.

Parabolic Antenna System: The parabolic antenna system is made up of two primary components, the dish itself, which is nothing more than a shaped mirror, and the feed. The feed is the portion of the system that "personalizes" the dish, give it a frequency band of operation. The feed must be properly tailored to the dish to insure that the "mirror" is illuminated in the correct fashion. The "illumination function" of the feed will establish the sidelobe performance and the beamwidth factor as noted previously. John Kraus's book "Radio Astronomy" has an excellent table in the back in Appendix 4, that relates illumination function to sidelobe level and beamwidth.

Focal length of Dish $f = D^2/16\, d$, where D is the diameter of the dish and d is the depth of the dish. A useful quantity: the f/D ratio defines depth of dish, tells you something about the feed needed to illuminate the dish. Typical f/D ratios for the satellite world are most commonly around, higher for flatter dishes (offset fed), and lower for older radar dishes where .25 was common, as they used dipole feeds.

Feed angle subtended, f/D is used as a shorthand to describe this and the feed type needed.
Dual polarization feeds often perform at a level of crosspolarization rejection less than expected due to polarization purity being corrupted by signal reflected back into the feed by the parabolic surface.

This article is by no means exhaustive and many more pages could be written, but it is the hope that the reader found some old material that he has become re-acquinted with and maybe a new tid-bit or two. 73!