The Physics and Design of Antennas

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Antennas are devices that allow for communication using electromagnetic waves. Although we have known how to build a basic antenna since the days of Maxwell, antenna design is still an area of intense research today. The advent of modern physics and computers has allowed us to design and build these devices in new shapes and out of new materials. Additionally, new research in materials has opened up the possibility of creating antennas that are able to survive some of the most extreme conditions in the universe. Advances in antennas design and materials will allow antennas to become smaller, faster, and smarter and enable new possibilities in communication. (7332 words)

I. INTRODUCTION

Although we have known how to induce electromagnetic waves for almost a century and a half thanks to Faraday and Maxwell, antennas have only become prevalent in our everyday lives over the past half-century or so. Simple antennas have been in use for over a century in analog radios. However, as computers, and now, laptops and cell phones have become increasingly important in our lives, the need for better, smarter, and smaller antennas has driven the development of many new technologies. Our modern smartphones may have as many as 4 or 5 antennas to accommodate GSM (Global System for Mobile Communications) or CDMA (Code division multiple access) cell technologies, WiFi, Bluetooth, GPS, NFC, and any other wireless technology the manufacturer wants to include.

Antennas, in their most basic form are simple devices; any wire will give off an electromagnetic wave if driven at high enough frequency since Maxwell showed us that an accelerating charge creates an electromagnetic wave. The trick is shaping and constructing the wire such that the radiation it gives off is aimed in the correct direction and is operating with minimum loss. When designing an antenna, one has to take into account the frequency at which the antenna will operate, the shape of beam it gives off, size and efficiency constraints, among other things. This is the challenge of designing antennas.

In this paper I will introduce about some fundamentals of electricity and magnetism that allow us to create antennas and electromagnetic waves in the first place. I will then talk some simple antenna geometries, including antennas created from conductors and aperture antennas. From there, I will describe using plasmas to create electromagnetic waves and the potential applications for this still burgeoning field. Finally, I will talk about some modern techniques used to design antennas, and some material considerations to take into account when designing an antenna, particularly for antennas deployed in hazardous locations such as on the exterior of spacecraft.

II. BASIC OPERATION OF ANTENNAS

A. Electromagnetic waves

The basic operation of antennas is relatively simple, but in order to understand how an antenna sends or receives a signal, it would be beneficial to first review the operation of electromagnetic waves. Electromagnetic waves are governed by Maxwell's equations. The two equations most relevant to electromagnetic waves are

$$\nabla \times E = -\frac{\partial \mathbf{B}}{\partial t}, \tag{1}$$

also known as Faraday's law of induction and

$$\nabla \times B = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}, \tag{2}$$

better known as the Maxwell-Ampere law [1], are functions of E, the electric field, B, the magnetic field, μ_0, the permeability of free space and ϵ_0, the permittivity of free space. Faraday's law tells us that a changing magnetic field will induce a electric field, while the Maxwell-Ampere law tells us that a changing electric field will induce an magnetic‘' field. Out of these equations, we find that an electromagnetic wave consists of a time-varying magnetic field generating a time-varying electric field, generating a time-varying magnetic field in a self-sustaining sequence. In addition, the magnetic field is orthogonal to the electric field and each field is orthogonal to the direction of travel [2]. These waves are the basis of wireless communication and what antennas ultimately seek to produce and capture.

B. Producing a Signal

All antennas operate on the same basic principle. To emit a signal, an alternating current pumped into the antenna produces an accelerating charge. To receive a signal, the AC signal generator is replaced with a small load [3]. As the signal generator creates a fluctuating potential in the antenna, we see by Faraday's law (Equation 1) that a changing magnetic field is induced, and thus our EM wave is created. If the antenna is driven with a constant AC source, a constant electromagnetic wave is produced. To receive a signal, an electromagnetic wave of the correct characteristics must pass by the receiving antenna; as it passes, the receiving antenna, the changing magnetic field of the wave induces a current in the antenna. An interesting and useful property of antennas is that the characteristics of a sending antenna are identical to those of an identical receiving antenna [3].

III. EVALUATING ANTENNA DESIGNS

Ultimately, designing an antenna for a particular application is, like anything else, a series a of compromises. There are several characteristics by which we can evaluate the trade-offs that are made while designing an antenna. One useful characteristic of antennas by which we can evaluate an antenna is the radiation pattern. The radiation pattern is a representation of the field strength by which an antenna receives or transmits. When talking about antennas, the radiation pattern generally refers to the radiation pattern in far-field, however, in some cases it is useful to evaluate the near-field (Fresnel) pattern. From the radiation diagram, we can determine the beamwidth, or the angle within which the power radiated is greater than $\sqrt{2}/2E_{max}$, where E_{max} is the maximum electric field strength [3–5].

Three other interrelated characteristic with which we can evaluate an antenna are the directivity, efficiency, and the gain. Directivity, D, defined by

$$D = U/U_0 \tag{3}$$

measures the maximum radiation intensity U of a given antenna compared to the radiation power U_0 of a theoretical isotropic radiator radiating with the same amount of power. Efficiency, η_a, defined by

$$\eta_a = P_{rad}/P_{in} \tag{4}$$

is simply the proportion of power radiated out of the antenna, P_{rad} compared to the power put into the antenna, P_{in}. Thus, $0 \leq \eta_a \leq 1$, where a value of 1 would indicate no ohmic losses in the antenna itself and all the power put into the antenna is radiated outwards, and a value of 0 would indicate all power put into the antenna is lost. Knowing directivity and efficiency, we can define the power gain (more commonly known simply as "gain"), G, of antenna:

$$G = \eta_a D. \tag{5}$$

Gain is the is the ratio of the maximum radiation intensity to the radiation intensity of an isotropic radiator supplied with equivalent power. We can more rigorously define directivity, efficiency and gain as [3, 4].

IV. THE HERTZIAN DIPOLE

A dipole antenna is an antenna which consists of two electrically separated linear conductors and is one of the most basic antenna designs. An idealized dipole is called a Hertzian dipole; this theoretical construct assumes that l, the length of the arms in the dipole is infinitesimally small. Since l is infinitesimally small, the the current flowing through the antenna is constant. Although a true Hertzian dipole is impossible to construct, it serves a reference point to which more complex antennas can be compared since arbitrary distributions of current can be modeled as superpositions of Hertzian dipoles [5].

To begin to analyze the Hertzian dipole, we can with Maxwell's equations. If the Hertzian dipole is situated in the center of our coordinate system and current all current is flowing in the $+\hat{z}$ direction as seen in Figure 1. We can then use Maxwell's equations to solve for the electric and magnetic field produced by the radiating dipole.

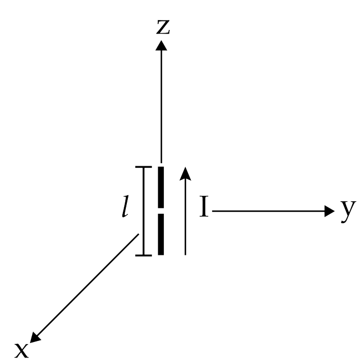

FIG. 1. Coordinate system for evaluating the Hertzian dipole. The infinitesimal current element is placed in the center of the spherical coordinate system with current flowing in the $+\hat{z}$ direction.

It can be shown the the electric field, $\mathbf{E}$ given off by the Hertzian dipole is defined by

$$\mathbf{E} = \frac{jk\eta}{4\pi}\frac{\exp(-jkr)}{r} Il\mathbf{u} \times (\mathbf{u} \times \mathbf{u}_D), \tag{6}$$

where I is the current flowing into the Hertzian dipole, k is the wavenumber of the electric signal being transmitted, $\mathbf{u}_D$ is the unit vector along which the dipole is oriented, and u is the direction at which an observer is looking [5]. η is an interesting characteristic called the "intrinsic impedance", and is a function of the medium in which an antenna is placed. In free space η is defined by

$$\eta = \sqrt{\mu_0/\epsilon_0} \tag{7}$$

and holds a value of approximately 377Ω. By name, it sounds like η might tell us something about the impedance of a vacuum, but what it actually tells us how the magnitude of the electric field compares to the magnitude of the magnetic field in an EM wave.

Using the relationship $\mathbf{E} = \frac{1}{j\omega\epsilon_0}(\nabla \times \mathbf{H})$, we can calculate that the magnetic field $\mathbf{H}$ to be

$$\mathbf{H} = \frac{jk}{4\pi}\frac{\exp(-jkr)}{r}Il(\mathbf{u}_D \times \mathbf{u}). \tag{8}$$

Using the theoretical expressions for the electric and magnetic field radiated by a Hertzian dipole, we can draw a radiation pattern, seen in Figure 2. We see that the radiation pattern for the Hertzian dipole is relatively undirected. The Hertzian dipole radiates both in front and behind of the actual antenna, and the half-power beamwidth is 90^o. This means that the directivity of a Hertzian dipole is 1.5; compare that to the directivity of an isotropic radiator with directivity of 1.

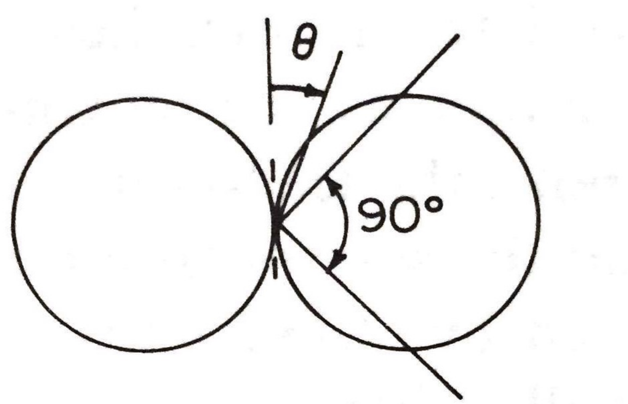

FIG. 2. Radiation pattern for a Hertzian dipole. The half-power points form a 90^o angle. The Hertzian dipole is not a highly-directional radiator; it's directivity is 1.5.

Because antennas are dissipating power in the form of electromagnetic waves, when placed in a circuit, they appear to have some resistance. This resistance, called the "radiation resistance", R_r, for a Hertzian dipole is given by [3, 5]

$$R_r = \frac{2\pi}{3}\eta\left(\frac{l}{\lambda}\right)^2 (\Omega). \tag{9}$$

Since η is known for an antenna operating in free space, the radiation resistance can be simplified to $800(l/\lambda)^2$. We see from this relationship that as the wavelength λ increases, the radiation resistance of the Hertzian dipole decreases. And in general, since in order for the theoretical model of the Hertzian dipole to work, $l << \lambda$, so the radiation resistance of the Hertzian dipole will always be very small.

Finally, the total power radiated, P_{rad}, by a Hertzian dipole can be shown to be [5]

$$P_{rad} = \frac{\pi}{3\lambda^2}\eta|Il|^2. \tag{10}$$

Equation 10 is also an important result for real dipoles (i.e. dipoles whose length is not infinitesimally small). It says in order for a dipole to be efficient such that it does not dissipate power through means other than radiation, the size of the antenna must be similar in size to the wavelength. Equation 10 explains that when dealing with low frequencies in a typical circuit, the wires in the circuit radiate a negligible amount of power. However, at very high frequencies, the wires in the circuit might start to radiate a non-negligible amount of power, so certain considerations have to be made while designing high-frequency circuits as to not cause interference. This makes sense because if $\lambda = \infty$, we no longer have an alternating current, and DC circuits do not radiate [3].

V. ANTENNA GEOMETRIES

A. The Dipole Antenna

A dipole antenna is similar to the Hertzian dipole in that it consists of two linear conductors that are electrically separated. Unlike a Hertzian dipole, the length, l, of its arms is not infinitesimal. If l is very, very small compared to the wavelength, λ, of the antenna, a dipole can be approximated as a Hertzian dipole. However, in cases where l is on the order of λ, additional analysis is required.

In a real dipole antenna, current is not constant across the entirety of the antenna as it is in the Hertzian dipole. For most dipoles, the current distribution can be approximated by

$$I(z') = I_M \sin\left[k\left(\frac{l}{2} - |z'|\right)\right], \tag{11}$$

where I_M is the maximum value of the current [3, 5]. Knowing what the current looks like at each point in the antenna, we can then integrate a series of Hertzian dipoles characterized by $I(z')dz$ along the length of the dipole to find the electric field radiated by an arbitrary antenna. Doing this calculation yields [5]

$$\mathbf{E} = \frac{j\eta I_M}{2\pi}\frac{\exp(-jkr)}{r}\frac{\cos(kl/2\cos\theta) - \cos(kl/2)}{\sin\theta}. \tag{12}$$

Since the first two terms in Equation 12 are constants, the third term can be used to characterize the far-field radiation of a dipole antenna as a function of the θ, the direction of observation.

In practice, most dipole antennas have arm lengths that evenly divide λ. One common configuration is the half-wave antenna. In other words, the length of the whole antenna has length $\lambda/2$, and each arm in the dipole has length $\lambda/4$. These antenna produce very distinctive radiation patterns; when $l \leq \lambda$, the radiation pattern shows only one lobe in each direction. When $l > \lambda$, multiple lobes appear in the pattern. Examples of the radiation pattern can be seen in Figure 3.

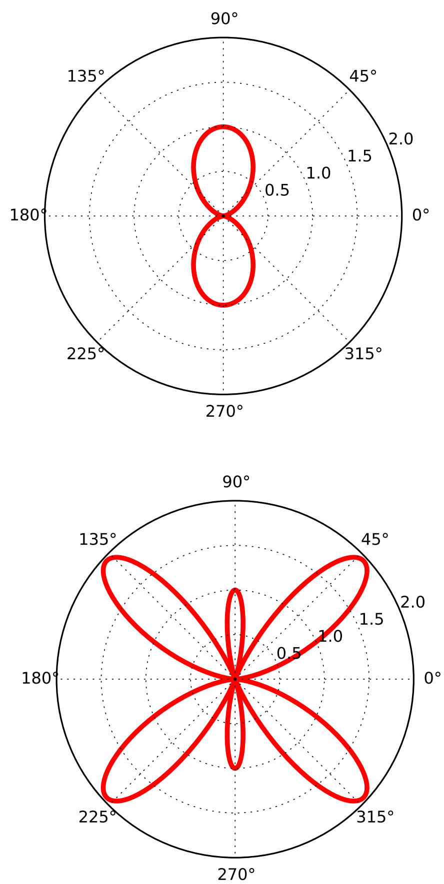

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FIG. 3. Radiation pattern cross-sections dipole antennas of length $l = \lambda/2$ (top) and $l = 3\lambda/2$ (bottom).

In order to compute the directivity of the a half-wave dipole, we first have to compute the radiation resistance for the antenna. For a half-wave dipole, the radiation resistance can be simplified to

$$R_r = \frac{\eta}{4\pi}\mathrm{Cin}(2kl), \tag{13}$$

where Cin is the "entire cosine integral" defined by

$$\mathrm{Cin}(x) = \int_0^x \frac{1-\cos(y)}{y}\,\mathrm{d}y. \tag{14}$$

We see that for a half-wave antenna with length λ, the radiation resistance is 73 Ω, and as the antenna gets shorter in length, the radiation resistance decreases [6]. Then, the directivity calculation for a half-wave dipole is relatively straightforward:

$$D = \frac{\eta}{\pi R_r}. \tag{15}$$

For a half-wave dipole with $l = \lambda$, the directivity is 1.64, which is slightly more directed than a Hertzian dipole which has directivity of 1.5 [6].

B. The Monopole Antenna

The monopole antenna, like the dipole antenna is another type of linear antenna. This antenna type consists of a linear conductor placed some height above, and perpendicular to an infinite conducting plane. The source signal is connected between the end of the conductor and the conducting plane [3, 4]. Monopole antennas are used most frequently for low and medium frequency applications such as TV and Radio broadcasts [6].

The operation of the monopole is effectively the same as the operation of the dipole antenna. The conducting plane creates an image of the monopole, so the current in the image behaves exactly as it would if the antenna had a second conductor. The result is that a monopole behaves exactly like a dipole of twice its length except the conducting plane cuts off half of the radiation pattern [3]. Thus, the amount of power radiated will only be half that of an equivalent dipole. But, because the power radiated is only half that of a dipole, the resistance is also halved, which means that the directivity is doubled as seen in Equation 15 [6].

One of the most common types of monopole antennas is the quarter-wave antenna; as their name suggests, the length of these antennas is $\lambda/4$. Large radio masts are generally quarter-wave monopoles used for broadcasting AM radio. For example, an AM radio broadcasting at 1 MHz, has a wavelength on the order of 300 meters, so these radio mast has to be on the order of 75 meters tall. These masts use the Earth as the conductor [6]. However, FM radio, TV, and cell phones broadcast signals on the order of GHz, so if these devices chose to utilize a monopole antenna, the antenna could be much smaller.

C. The Yagi-Uda Antenna

Many times, when trying to achieve greater directivity or gain from a dipole antenna, arrays of dipoles are constructed. The most common dipole array is the Yagi-Uda antenna, named for its inventors. This type of antenna is commonly used as a receiving antenna for Television signals. The layout is simple: multiple dipoles are placed parallel to each other along an axis. The first dipole is longer than the rest as it is meant to serve as a reflector. The second dipole in the line is the dipole that is driven. The remaining dipoles are slightly shorter than the the first two dipoles and are parasitic and act as directors [6]. Since the directors and reflector are not driven, they are sometimes called parasitic in that they are not electrically connected to anything and simply radiate passively. In general, the reflector is about 5% longer than the driven element and the directors are about 5% shorter than the driven element. The parasitic elements are usually spaced on the order of 0.15λ to 0.25λ [3]. A five-element Yagi-Uda array can be seen in Figure 4. Yagi-Uda antennas are notable as they provide good directionality while maintaining a simple structure.

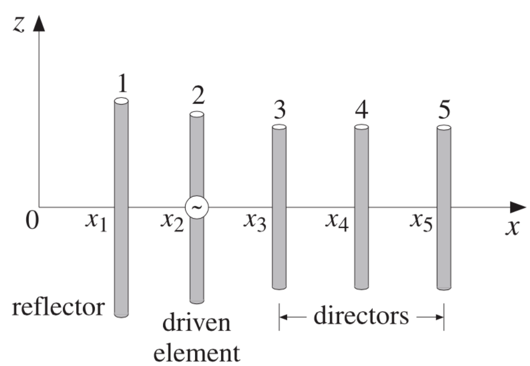

FIG. 4. A five-element Yagi-Uda antenna.

It's not possible to analyze Yagi-Uda antennas analytically; rather, numerical methods must be used. However, for a three-element Yagi Uda antenna (i.e. one reflector, one driven element, and one director), the maximum gain of this type is antenna is around 9.8 dB. Compare this to a perfectly efficient half-wave dipole, which would have a gain of 1.64 dB. While adding extra reflectors is relatively useless, adding extra directors can increase the directivity and gain, however, there comes a point of diminishing returns where adding a extra directors becomes useless. One interesting modification of a Yagi-Uda array is to replace the reflector dipole with a sheet of metal. The sheet of metal will almost completely prevent any radiation from traveling behind the antenna. The sheet of metal also has the advantage of being fairly frequency insensitive [3].

D. Other Antenna Geometries

The dipole and monopole antennas and their derivatives and modifications, such as the Yagi-Uda antenna, while simple and effective, are by far not the only geometries used. One such geometry is the helical antenna. The simplest helical antenna is simply a wire wound in the shape of a helix. Varying the diameter of the helix, the diameter of the wire, or the pitch or number of turns in the helix can change its radiation characteristics. If the helix is short compared to the wavelength, it operates similar to a dipole. If the helix diameter and pitch are large compared to the wavelength, then radiation comes off the end of the antenna rather than outwards. The radiation emitted in this mode is circularly polarized [7].

Loop antennas are, as their name suggests, loops of wire, but they can be squares, circles, or any other shape. A "small" loop is a loop antenna where the area of the loop is less than $0.01\lambda^2$. In a small loop, we can assume that the current is constant around the loop and the same as the current at either terminal of the antenna. The electric field of a small loop turns out to be the same regardless of the shape of the antenna. Small loops are fairly undirected antennas, with directivity around 1.5, and their radiation resistance is very low, given by [4]

$$R_r = 320\pi^4 A^2/\lambda^4. \tag{16}$$

So, for example, receiving AM radio waves at around 1 MHz, the radiation resistance is about $2 \times 10^{-8}\Omega$. Loop antennas are poor radiators, so they are almost never used as a transmitting antenna. Small loops are used as receiving antennas at low frequencies, such as for AM radios [3].

E. Frequency Independent Antennas

All the antenna types discussed so far have had their characteristics defined by the ratio between the length of the antenna itself and the frequency of signal sent or received. Generally, this kind of behavior is desired as it eliminates the amount of noise an antenna can receive. However, there are applications where a frequency independent antenna would be desired. One such application is for ultra-wideband communications; ultra-wideband antennas would enable fast data transfer over short distances by efficiently utilizing a large portion of the frequency spectrum [8].

Frequency independent antennas have no real characteristic length [3, 8]. As they have no characteristic length, frequency independent antennas are defined completely by angles and the antenna has to be infinite in size. But, we clearly can't have an antenna infinite in size. So, in

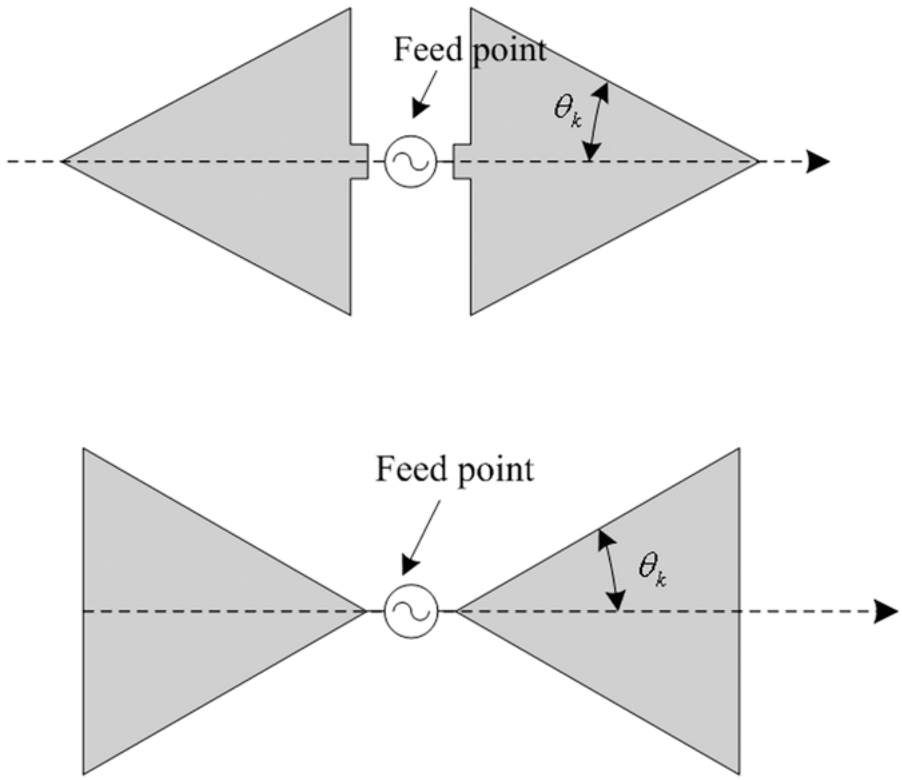

FIG. 5. A diamond antenna (top) and bow-tie antenna (bottom) are two frequency independent antennas [8].

order to make one of these antennas frequency independent, the antenna has to appear "effectively infinite" to the current.

One of the simplest frequency antennas is the 2D biconical antenna, otherwise known as a "bow-tie" or "diamond" antenna (seen in Figure 5). This antenna is made up of two opposing triangular pieces and is fed in the middle. Since we can't make an infinite antenna and the gap between the middle of the triangles where the feed connects cannot be infinitesimally small, the antenna does end up with some characteristic length which limits its frequencies [3, 8]. If the dimensions of the antenna are chosen cleverly, experimentation has shown that bow-tie antennas which can operate on carrier frequencies between 3.1 and 10.6 GHz can be produced [8].

One other frequency independent antenna that bears mentioning is spiral antenna. The spiral antenna is an antenna made up of two spirals spiraling in opposite directions. The equation [3]

$$r = r_0 \exp\left[a(\phi - \phi_0)\right], \tag{17}$$

where r_0, ϕ_0, and a are arbitrary constants, defines what's called an equiangular spiral since the angle between the radius vector and the tangent to the curve has the same angle for all points along the spiral. We can use four equiangular spirals with ϕ_0 corresponding to 0, $\pi/2$, π, and $3\pi/2$ to create spirals which are all connected at the origin and define regions in which to construct an antenna. Intuitively, this antenna should be frequency independent because if a spiral were to shrink or grow by any factor, the shape would remain the same. Again, though, we have to pick some length at which to cut off the antenna. Experimentation has shown that in this geometry of antenna, the current seems to die off rapidly beyond $r \approx \lambda/2$. So, if the antenna is cut off at something like $r \approx \lambda$, the antenna would appear effectively infinite for wavelengths less than λ [3].

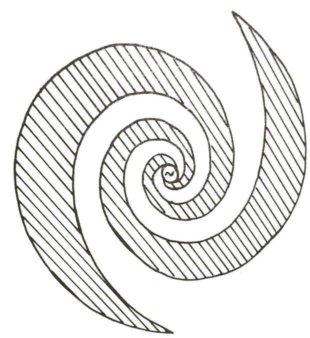

FIG. 6. An equiangular spiral antenna, another frequency-independent antenna [3]. This antenna works for all wavelengths up to about the length of its arms.

There are of course more geometries for frequency-independent antennas. Unlike many other simple antenna geometries, frequency-independent antennas, with the exception of the log-periodic dipole, are almost impossible to model analytically. All we know about the characteristics of frequency independent antennas was learned through simulations or experimentation.

F. Aperture Antennas

Only antennas through which current flows have been discussed so far, however there is another class of antennas called aperture antennas. The most basic aperture antenna is the slot antenna. A slot antenna is simply a hole cut in the middle of a conductor. This type of antenna produces radiation similar to a dipole except its radiation is polarized differently from a dipole. If the sheet of conductor is turned into an open box, radiation only emerges out of the box. If the box is flared, a horn antenna is produced [4]. Horn antennas operate in a similar manner to acoustic horns. Horn antennas are used frequently in satellites due to their ability to produce very wide beams [7].

Horn antennas can also be used in conjunction with a reflector antenna. This antenna is the "dish" antenna used for satellite TV reception, radio astronomy, or on spacecraft. The reflector in

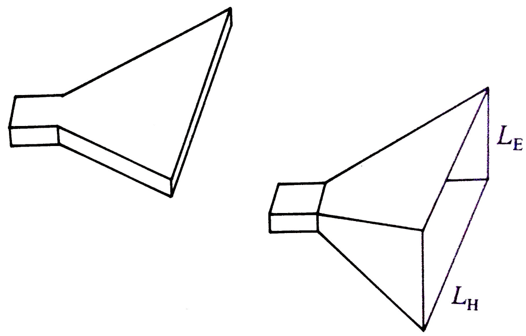

FIG. 7. Two simple horn antenna geometries [4].

a reflector antenna is typically a sheet of conducting material. The reflector can be shaped into a plane, 90° corner reflector, or a parabola, among other shapes. The horn transmits directly at the reflector where the reflector antenna increases the gain by narrowing the beam while creating uniform plane waves in the desired direction. For receiving, a reflector antenna focuses a larger amount of radiation to a single point such that a weaker signal can be picked up. As long as the reflector is large compared to the wavelength, the gain will be large [4, 7]

VI. MATERIALS SUITABLE FOR ANTENNA USE

In regards to metallic antennas on earth, most conductors will serve as an antenna. For an antenna, we of course need a material that is highly conductive and malleable. Hence, some of the most common materials of which antennas are silver, copper, aluminum, and other abundant metals. However, in extreme conditions, these materials will degrade or erode, and that's a problem, especially when they can't be replaced. There are several other classes of materials that can, and do serve as antennas. Spacecraft antennas are one area where special consideration has to be made with regards to materials choice as there aren't too many conditions more punishing than outer space. Antennas on spacecraft are always on the exterior of the craft, and thus are subject to abuse from photons with energy up to several hundred MeV, cosmic rays, UV radiation, residue from propellants or other fluids dumped from the craft, and huge temperature swings. In addition, these antennas must be able to survive any vibration or thermal fluctuation during launch [7].

Of course, the most important function of an antenna is its ability to transmit or receive signals, so therefore, most, if not all of the antenna has to made of a conductor. Most antennas, whether located on a spacecraft or not, are not made from ferrous alloys such as irons and steels due to their weight, low electrical conductivity, and susceptibility to corrosion. [9]. On earth, metals like copper or magnesium work fine. For more challenging environments, such as outer space, antennas are made out of some sort of alloy. Some subset of aluminum, beryllium, magnesium, or copper alloys are popular choices for antennas. There are numerous alloys to choose from, so the choice of alloy depends on the mission of the spacecraft [7]. Since each alloy has different thermal and electrical properties, there is never one "correct" answer as to which material to choose.

In the case of reflector-type antennas, polymer-matrix composites or ceramics are generally preferred. Polymer-matrix composites are a class of materials that consist some sort of fiber inserted into a polymer resin to reinforce the polymer matrix structure. These composites are desirable because they are very stiff, have high thermoelastic stability, and they are customizable during the manufacturing process [7]. There are several classes of material that can be used as the reinforcement in these types of composites. One material that is commonly used in polymer-matrix composites is fiberglass. Glass fibers of diameter somewhere in the range of about 3 and 20 μm are laid out in the polymer matrix to produce an very stiff material. However, glass fiber-reinforced polymer composites are not the stiffest composite possible, and they don't perform well at high temperatures [9]. For this reason, they are not that widely used as spacecraft antennas. Carbon fiber-reinforced polymer composites, on the other hand, solve most of the problems of fiberglass composites. Carbon fiber has the highest specific strength of any reinforced fiber material and they are very resistant to temperature, radiation, moisture, acids, and bases [7, 9]. Carbon fiber materials are quickly becoming widely used as reflector antennas in spacecraft. While fiberglass materials are inexpensive, carbon fiber is very expensive and complicated to manufacture.

Ceramic antennas are a new development, but are quickly becoming widespread. Ceramics are a class of material that is some sort of mixture between a metallic and non-metallic elements. Two of the most commonly used ceramics are carbon-carbon (C-C) and silicon carbonide (SiC). These materials are used not only as antennas on spacecraft. For example, the reentry heat shield tiles on the space shuttle were made from a high-performance carbon-carbon. These materials are incredibly lightweight and resistant to all kinds of radiation. Their only drawback is that they are very brittle and prone to catastrophic failure [9]. Thus, when using ceramics on a spacecraft, the antenna has to be incredibly protected and isolated, especially during takeoff.

VII. PLASMA ANTENNAS

Modern research into plasmas has enabled an entirely new class of antennas with very favorable characteristics. While we can make wideband antennas using wire antennas, performance of these antennas are not as good as they could be if the antenna were designed for a single band. Plasma antennas, while not currently ready for widespread use, allows for a single antenna to be reconfigured to a specific frequency, radiation pattern, direction, or beamwidth on the fly. The reconfigurable nature of plasma antennas is exciting since it plasma antennas could theoretically replace multiple antennas in one device. In terms of performance, plasma antennas could greatly exceed the performance of metal antennas both in terms the signal-to-noise ratio and the physical size of the antenna [10]. Plasma antennas are also of great interest due to their applications in the military. The ability of a plasma antenna to be switched off means the antenna effectively disappears, making a plasma antenna invisible to radar [11].

A. Basic Plasma Physics

In order to understand a plasma antenna, it would be beneficial to first understand some basic plasma physics. In the simplest terms, a plasma is simply an ionized gas. While plasmas in nature generally exist in stars as gases at temperatures above 100,000K, it is possible to create a plasma at much, much lower temperatures. In a plasma, electrons at rest "shield" ions as the electron at rest repels other electrons. This essentially creates a sphere of influence for a given test charge in a plasma called the Debye length. The Debye length, λ_D is defined by

$$\lambda_D = \frac{K_B T}{8\pi n e^2}^{1/2}, \tag{18}$$

where K_B is Boltzmann's constant, T is the temperature of the plasma in Kelvin, n is the density of electrons, and e is the fundamental charge [12].

Another characteristic of plasmas that is useful to understand in the context of plasma antennas is the plasma frequency, ω_p, defined as

$$\omega_p = \left(\frac{4\pi n e^2}{m_e}\right)^{1/2}. \tag{19}$$

Intuitively, the plasma frequency measures how long it takes an electron or ion moving at thermal speed, defined by $(K_B T/m_e)^{1/2}$ [13], to travel one Debye length. The plasma frequency is also useful in characterizing a plasma based on its electron density [12].

When an electromagnetic wave comes in contact with with a rectangular slab of plasma, the reflection and transmission coefficients can be defined as

$$R = \frac{k_0 - k_p}{k_0 + k_p} \tag{20}$$

$$T = \frac{2k_0}{k_0 + k_p}, \tag{21}$$

where k_0 is the wavenumber of the incident wave and k_p is the wavenumber of the electromagnetic wave in the plasma. If ω is the angular frequency of the electromagnetic wave outside of the plasma, if the density of the plasma is high enough such that $\omega << \omega_p$, then we see that R goes to -1 and T goes to 0. So the plasma reflects waves below the plasma frequency as if the plasma were a perfect conductor. On the other hand, if $\omega >> \omega_p$, we see that R goes to 0 and T goes to 1, so the electromagnetic wave passes through the plasma. However, if ω is on the order of ω_p, we get scattering and conductivity [10].

B. Creating a Plasma Antenna

To create a plasma antenna, we first have to create a plasma. Plasmas can be created in any number of ways; plasmas can be created by applying an electric or magnetic field, applying heating, or by laser excitation [10]. Many times, plasma antennas are constructed from cylindrical columns of plasma whose radius is much smaller than the incident electromagnetic wave. The plasma must be chosen such that the angular frequency of the electromagnetic wave to be sent or received is larger than the the plasma frequency, otherwise the wave will simply pass through the plasma, as shown in the previous section. Picking an antenna frequency twice that of the plasma frequency is a common choice [10]. Since plasmas conduct, creating an antenna out of plasma is very much the same as creating an antenna out of metal. To transmit a using a plasma antenna, a surface waves– electromagnetic waves that are strongly guided along the plasma-vacuum barrier [12]– are created. These waves act in a similar manner to the the guided waves in a metallic dipole antenna, the only difference being for driven frequencies near the plasma frequency, the phase velocity becomes much less than the speed of light [11].

C. Nesting and Smart Plasma Antennas

Recall that if an electromagnetic wave with angular frequency ω is incident on a plasma antenna with plasma frequency ω_p and $\omega >> \omega_p$, the reflectivity of the plasma goes to 0 and the transitivity goes to 1, i.e. the electromagnetic wave passes straight through the plasma. We can use this fact to our advantage by nesting antennas. Plasma antennas can be placed inside of each other with the highest frequency antenna at the center and the lowest frequency antenna on the outside. If the plasmas are chose appropriately, the high-frequency antennas can transmit and receive through the low-frequency antennas. With metallic antennas, a low-frequency antenna would interfere with a high-frequency antenna if placed to close. There will undoubtedly be some interference with nested plasma antennas, but that too can be completely eliminated since plasma antennas can be switched on and off [10].

Another unique feature of plasma antennas is the ability to create a “smart” antenna. These antennas utilize the ability of plasma to completely reflect electromagnetic waves. The concept of smart antennas is to place a blanket of plasma whose density can be varied around an omni-directional antenna. Again, if the plasma frequency is high compared to the antenna frequency, waves will be completely reflected, but if the plasma frequency is low, waves will be allowed to pass through. In practice, what this looks like is a ring of plasma tubes surrounding an antenna. Each plasma tube is effectively a “window” which can choose to let radiation through by lowering or raising the density of plasma. This setup allows for beam steering and reconfigurable directivity by selectively choosing which windows, and the number of adjacent windows, are open [10]. These smart antennas are of great interest to the aviation and naval industries as well as the military since a single “smart” antenna, when combined with a nested antenna, could replace large arrays or multiple dish-type antennas in locations where space is at a premium.

D. Thermal Noise

Plasma antennas are also substantially better than their metal counterparts at high frequencies since they exhibit less of an effect from thermal noise. Consider if we had a one-dimensional strip of a conductor of length L, then the number of quantum states in the conductor is given by

$$2\int \frac{dx dp_x}{h}, \tag{22}$$

where p_x are the momentum quantum states available in the x direction and h is the Planck constant. Since the integral from 0 to L of dx is simply L, and using $E = hf = pc$, Equation 22 can be rewritten as

$$\frac{2L}{c}\int df, \tag{23}$$

where f is the frequency of the wave traveling through the conductor. Then, the average energy in each quantum state is the product of the energy per wave (again, $E = hf$), and the occupation number. If we model this system as a blackbody radiator, then the occupation number becomes

$$\bar{n} = \frac{1}{e^{\beta\epsilon} - 1}, \tag{24}$$

where $\beta = (K_B T)^{-1}$ and ϵ is the average energy in each state. We know that $\epsilon = E = hf$, so the thermal energy carried in each electromagnetic wave becomes

$$E_{\text{thermal}} = \frac{2L}{c} \int df \frac{hf}{e^{hf/K_B T} - 1}. \tag{25}$$

If we're only interested in dealing with frequencies such that $hf << K_B T$, then we can use the first order expansion of e^x as $e^x \approx 1 + x$ to simply this integral. This is a pretty good approximation, as this assumption is valid up until about 10^{12} Hz at room temperature. Carrying out this substitution yields that

$$\frac{hf}{e^{hf/K_B T} - 1} \approx K_B T, \tag{26}$$

for small f. Substituting Equation 26 into Equation 25 and integrating over Δf gives us

$$E_{\text{thermal}} = \frac{2L}{c} K_B T \Delta f. \tag{27}$$

On average, a wave at arbitrary position in the conductor must travel half the length of the conductor. Traveling at the speed of light, that means that it would take a wave $t = L/2c$ time to exit the conductor. Now, we can find the power of the thermal energy. By definition, power is the work divided by time, so

$$P = \frac{\text{work}}{\text{time}} = \frac{2L/cK_B T \Delta f}{L/2c} \tag{28}$$

$$P = 4K_B T \Delta f. \tag{29}$$

Finally, for circuits, $P = \bar{V^2}/R$, so we arrive at

$$\bar{V^2} = 4K_B T R \Delta f. \tag{30}$$

If we're interested in knowing the power spectral density, which describes the variance of noise at each frequency, we set $\Delta f = 1$ and find

$$\bar{V^2} = 4K_B T R, \tag{31}$$

which is the well-known expression for Nyquist-Johnson noise, also written as $H(f)$ [14]. However, for plasma antennas, this equation is not sufficient because of the assumption made in Equation 26.

As stated previously, this approximation works for low frequencies in metals because the collisions between electrons is on the order of terahertz. However, in a plasma, we have to take into account the collisions between atoms in the gas collide much less frequently [10].

Thus, is a correction term is necessary to fully analyze the thermal noise of a plasma antenna. The correction term can be found to be

$$1/(1+\omega^2/v_{cc}^2). \tag{32}$$

So, the full expression for power spectral density for a plasma antenna is found to be

$$H(f) = 4K_BT\frac{R}{1+\omega^2/v_{cc}^2}, \tag{33}$$

where v_{cc} is the frequency of electron-gas collisions in the plasma. As a sanity check, in a metal antenna, $v_{cc} >> \omega$, so the correction goes to 1, and we get back Equation 31.

From these equations, we can see why plasma antennas perform better at higher frequencies than their metal counterparts. For example, take a hypothetical 3 cm long copper antenna with with a 1 cm square cross section broadcasting at 10GHz, $H(f) = 1.04\exp(-21)$ V^2/Hz. Compare that to a hypothetical plasma antenna constructed from a fluorescent light operating at the same frequency which has noise given by $H(f) = 4.29\exp(-24)$ V^2/Hz [10]. Notice that in this back-of-the-envelope calculation, the plasma antenna has 3 orders of magnitude less noise than the metal antenna. Of course, that means that at low frequencies, the traditional metal antenna will perform better. However, since this calculation was done based on the properties of a fluorescent light tube, which are not purpose designed as an antenna, may show higher thermal noise than a custom plasma tube operating at low pressure [10].

E. Silicon-Based Plasma Antennas

Another type of reconfigurable antenna design that has been proposed is based on silicon. In this design, the plasma tubes are replaced with silicon-based lateral PIN diodes. PIN diodes are semiconductors that consist of three regions: an undoped "intrinsic" region is placed between a heavily doped p-type semiconductor and a heavily doped n-type semiconductor. In a lateral PIN diode, the doped regions are placed into the intrinsic region and contact pads are placed on doped portions. A lateral PIN diode can be seen in Figure 8.

A plasma antenna is constructed from surface lateral PIN devices (coined SPIN devices). A SPIN device is constructed from high-resistivity silicon in order to maintain a high carrier lifetime

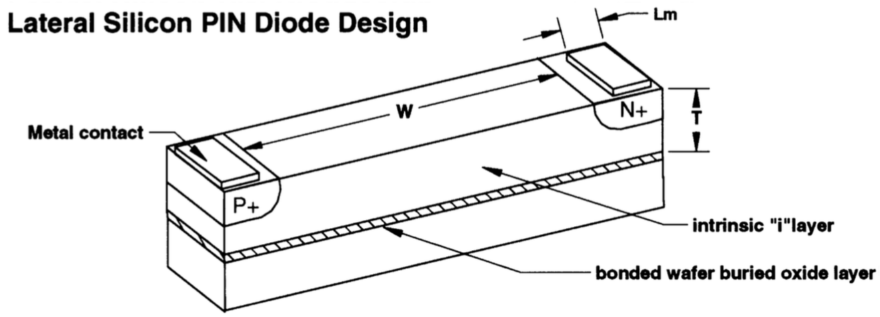

FIG. 8. A lateral PIN semiconductor [15]. When operated a current is placed through the diode, the high resistivity of the intrinsic layer causes a steady-state plasma to form on the surface of the intrinsic layer.

on the surface of the diode. SPIN devices are designed such that all the free carriers are concentrated in the top surface of the diode. By choosing a good set of dimensions, doping concentrations, and boundary layers, the concentration of carriers in the SPIN device can reach $10^{18}/cm^3$ with limited current. In the on state, free carriers under forward bias creates a steady state plasma. Since the charges are highly mobile when the diode is turned on, the intrinsic region mimics a metallic conductor. In the off state, the intrinsic region exhibits high resistance. Thus, by creating an array of these SPIN devices, a reconfigurable plasma antenna is made. The grid of diodes can create any antenna shape simply by switching on and off these diodes [15].

There are several companies already working implementing this idea for consumer use, coined the “Plasma Silicon Antenna”, or PSiAN for short. Since there can be tens of thousands of diodes on each antenna chip, many antennas configurations can be created on the fly. The most important consequence of this is that the antenna can change the shape and steer their beam. The potential applications for PSiANs are almost endless; they are small enough to be placed in laptops, cell phones, WiFi routers, and many other consumer devices. The ability to steer the beam would enable faster, more power efficient wireless communication. In addition, these antennas could also be deployed as small, inexpensive radar and placed into cars as a driver-assistance feature [16].

F. Applications

Plasma antennas are still in their infancy and many labs and companies are working on developing plasma antennas for both civilian and military use. As mentioned before, there are submarines and stealth planes would really benefit from plasma antennas. In order to communicate with submarines, very long wavelengths have to be used since shorter wavelengths have a hard time penetrating water. Ideally, to communicate with a submarine, one would like to use frequencies less than 3 kHz, in the so-called "Extremely Low Frequency" (ELF) band. However, a transmitter for a 3 kHz signal using even a quarter-wave design would need to have an antenna 25 km long! Thus, in order to transmit to a submerged submarine, one has to either lay a very long cable in the ground or use a balloon to lift a cable up to an enormous height. Since ELF communication is not yet possible, to receive a signal, submarines must use large mast-mounted antennas or tow buoys to receive a signal. Neither of these solutions are ideal as an antenna takes up valuable space on the mast of submarines, and towing an antenna means the submarine has to slow down. Furthermore, submarine communication is one-way since it would be impossible for submarines to carry a transmitter multiple kilometers long [17]. Plasma antennas make possible the ability to communicate on ELF frequency, because recall all that's needed for a plasma antenna is a column of ionized gas. Although plasma antennas that have been discussed prior exist in glass tubes, this requirement isn't strictly necessary. So, where does one find a 25 km long column of plasma? It turns out that we can make one by directing a high-powered laser at the ionosphere. A high-powered CO_2 or Nd:YAG laser could theoretically ionize an air column directly above it such that radio signals could be transmitted off of the ionized air. Another possibility is to use a powerful magnetic field to induce drift currents in a plasma tube. If a Helmholtz coil is placed in a plasma tube and the tube is oriented horizontally to the ground, the plasma ions will feel the force of gravity perpendicular to the magnetic field, and the plasma ions will feel a drift current [17]

$$\mathbf{v}_{DG}^{\alpha} = \frac{m_\alpha}{q_\alpha} \frac{\mathbf{g} \times \mathbf{B}}{q_\alpha B^2} c, \tag{34}$$

where m_α and q_α are the mass and charge of a charged particle in the plasma. Then, if the magnetic field is oscillated, a large current will be induced in the plasma due to the drift current of the ions. Theoretically, this current could be much larger than any current that could be possibly put into a traditional metallic antenna. Since the current is larger, the physical antenna could be shorter. If a high enough current could be achieved via this method, the plasma antenna could be portable, or even installed on a submarine allowing for bidirectional communication on ELF frequencies even when the submarine is submerged [17].

Another reason the military is interested in plasma antennas is interested in plasma antennas is due to their low radar cross section [10]. Radar works by bouncing radio waves off and object and looks for any sort of response returned to the radar dish. Although planes can be designed to avoid radar detection, communications systems on these aircraft are still a major problem as metallic antennas reflect radar. However, plasma antennas suffer no such problem. As mentioned in Section VII A, as the plasma frequency decreases, the transmission coefficient of the antenna increases, and the antenna becomes transparent to more and more frequencies of electromagnetic waves. Thus, if a plasma antenna could be designed to transmit on wavelengths longer than radar, the radar waves would pass right through the plasma and the aircraft would remain undetected. Even for traditional frequencies, plasma antennas are advantageous due to their ability to be switched off. If the aircraft wishes to fly in stealth mode, it could simply switch its antenna off and fly undetected [10].

VIII. DESIGNING ANTENNAS ALGORITHMICALLY

It's impossible to design any real antenna completely analytically because the solutions to many of of the equations governing antennas are simply too complex, so computational approximations have to be used. Until very recently, most antennas were designed by hand. One would start with a known antenna design, and tweak the design and continuously test until the design parameters were met. However, designing an antenna by hand requires very specific knowledge and a lot of time. Designing has almost always required a computer to model the antenna, but all the input design parameters were given by humans

More recently, the design of antennas has been done by evolutionary algorithm. Evolutionary algorithms are a class of algorithm that attempts to mimic natural selection. The basic concept is simple: design constraints and an initial antenna design is input into a computer. The computer makes some random change to the antenna and reevaluates its performance. If the performance of the randomly-permuted antenna is better than the previous iteration, the new design is kept, otherwise it throws it out. Although research into this technique dates back to the 1990s, this technique has only become more feasible due to the greater availability of powerful computer hardware. Genetically evolved antennas are advantageous simply because a computer can create far more designs than a human can in a much shorter amount of time. Evolutionary algorithms can also take into account interference due to structures surrounding the antenna, something that be almost impossible by hand, while searching for a design [18].

The first deployed genetically evolved antennas was launched into space in 2006 aboard NASA's Space Technology 5 (ST5) satellites. NASA had originally contracted a designer to produce an antenna for the ST5 satellites. These designers came up with a quadrifilar helix design. Two antennas, mounted on the top and bottom of the spacecraft, the quadrifilar helix system achieved 38% efficiency. NASA then brought in computer scientists who designed a genetic algorithm

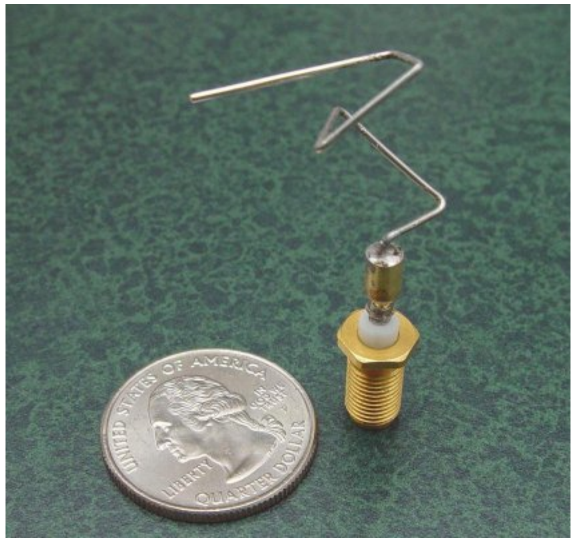

FIG. 9. The evolved antenna developed for the ST5 mission [18].

that designed an antenna consisting of 4 genetically evolved, identical monopoles. The mission requirements were then changed, as the satellites were supposed to fly in much lower orbit, so a new antenna was evolved. The new antenna contained only 1 arm, and it took about a month to make the changes to the algorithm to develop a new antenna. When tested, one of the evolved antennas working in combination with the quadrifilar helix produced an 80% efficient system while two evolved antennas produced a 93% efficient system [18].

IX. CONCLUSION

Antennas allow us to communicate by means which would have been unthinkable even just one century ago. At the turn of the 20th century, radio was just starting to become common, but today, we are able to transmit digital information at incredibly high speeds through the air with minimal power draw. While its incredibly easy to create *an* antenna, it is very hard to create a *good* antenna. The complexity of the theory involved in analyzing an antenna analytically have made it challenging and time consuming to create unique antenna geometries. However, the advent of computers has allowed us to more quickly analyze the performance characteristics of a particular design. Going forward, computers will be able to fully design antennas for us given a set of constraints, hopefully making high performing antennas cheap and easy to produce. As we understand more about plasmas, plasma antennas could become as ubiquitous and inexpensive metallic antennas are today. Plasma antennas could enable a whole new generation of technologies thanks to their ability to beamform or operate at multiple frequencies. Finally, as we improve our manufacturing processes, high performing composite materials could pave the way for a new generation of spacecraft that is able to communicate at terahertz frequencies and transmit more data back to Earth. As time goes on, antennas are only going to become smarter and more and more prevalent to the point where wires may become completely unnecessary.

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[1] E. M. Purcell, *Electricity and Magnetism*, third edition ed. (Cambridge University Press, 2013), URL: `http://assets.cambridge.org/97811070/14022/cover/9781107014022.jpg`

Annotation: I used Purcell as an interpretation of Maxwell's equations and their implications on electromagnetic waves.

[2] J. C. Maxwell, *A Dynamical Theory of the Electromagnetic Field*, Philosophical Transactions of the Royal Society of London **155** (1865), pp. pp. 459–512,
URL: `http://www.jstor.org/stable/108892`

Annotation: I referenced Maxwell's original paper for an interpretation of Faraday's and Ampere's law.

[3] K. F. Lee, *Principles of antenna theory* (Wiley, Chichester, 1984)

Annotation: I used this source a lot because it provided a wealth of information on the design of traditional antenna gemoetries. Each section in the book provided a nice high-level explanation as to what was going and some easy to follow derivations.

[4] J. Griffiths, *Radio wave propagation and antennas: an introduction* (Prentice Hall, Englewood Cliffs, N.J., 1987)

Annotation: This book mainly talked about how the waves leaving an antenna propagate, but the introduction provided some nice information about the type of radiation released by various simple antenna geometries.

[5] S. Drabowitch, *Modern antennas*, 2nd ed ed. (Springer, Dordrecht, 2005),
URL: `http://www.loc.gov/catdir/enhancements/fy0663/2006273254-d.html`

Annotation: This was an advanced textbook that covered a broad spectrum of topics relating to the physics behind the operation of antennas. Some of the topics discussed were too complicated for the scope of this paper, but it provided a nice overview on the different types of antennas and some of their characteristics.

[6] S. J. Orfanidis, *Electromagnetic Waves and Antennas* (2014),
URL: `http://eceweb1.rutgers.edu/~orfanidi/ewa/orfanidis-ewa-book.pdf`

ANNOTATION: This is a nice but very engineering-focused book on the operation of many types of antenna geometries. I liked this book because provided a lot of real examples and computational analysis.

[7] W. A. Imbriale, S. Gao and L. Boccia, *Space antenna handbook* (John Wiley & Sons, Chichester, West Sussex, 2012)

ANNOTATION: This book provided information regarding antennas placed on spacecraft. The section I was interested in was mainly a list of materials used in space-based antennas, so I combined this book with other sources on materials science.

[8] D. Valderas, *Ultrawideband antennas: design and applications* (Imperial College Press, London, 2011)

ANNOTATION: I used this book primarily in researching frequency-independent antenna designs. Although this book was focused primarily on the applications of frequency-independent antennas, it provided a nice high-level overview of the topic.

[9] J. William D. Callister, *Materials Science and Engineering*, 5 ed. (Wiley, 2000)

ANNOTATION: This textbook provided some nice background on the process and logic behind alloying metals. It was also useful in defining what polymer-matrix composites and ceramics actually are.

[10] T. R. Anderson, *Plasma antennas*, Artech House antennas and propagation series (Artech House, Boston, 2011)

ANNOTATION: This book provided a broad range of information regarding the benefits, operation, and physics behind plasma antennas. It was written by the same former Navy scientist who wrote the Navy paper cited.

[11] G. G. Borg, J. H. Harris, N. M. Martin, D. Thorncraft, R. Milliken, D. G. Miljak, B. Kwan, T. Ng and J. Kircher, *Plasmas as antennas: Theory, experiment and applications.*, Physics of Plasmas **7** (2000) (5), pp. 2198 – 2202,
URL: `http://search.ebscohost.com/login.aspx?direct=true&db=keh&AN=4416729&site=ehost-live`

ANNOTATION: This paper provided a method for coupling in EM waves into a column of plasma to actually make an antenna.

[12] N. A. Krall and A. W. Trivelpiece, *Principles of plasma physics* (McGraw-Hill, New York, 1973)

ANNOTATION: I used this book as it nice background on plasma physics especially when researching the plasma frequency or Debye length.

[13] A. Piel, *Plasma physics: an introduction to laboratory, space, and fusion plasmas* (Springer, Heidelberg, 2010)

ANNOTATION: This book was referenced by the plasma antennas book, and it was helpful in determining things like the thermal speed.

[14] K. S. Stowe, *An introduction to thermodynamics and statistical mechanics*, 2nd ed ed. (Cambridge University Press, Cambridge, UK, 2007),
URL: `http://www.loc.gov/catdir/enhancements/fy0803/2007298684-b.html`

ANNOTATION: I used the Thermo textbook to aid me in the derivation of the Nyquist-Johnson noise in antennas.

[15] A. E. Fathy, A. Rosen, H. S. Owen, F. McGinty, D. J. McGee, G. C. Taylor, R. Amantea, P. K. Swain, S. M. Perlow and M. ElSherbiny, *Silicon-Based Reconfigurable Antennas—Concepts, Analysis, Implementation, and Feasibility*, IEEE Transactions on Microwave Theory and Techniques **51** (2003) (6), pp. 1650–1661

ANNOTATION: This paper describes using semiconductor diodes to create reconfigurable plasma antennas.

[16] D. Hambling, *Wireless at the speed of plasma* (2010),
URL: `http://www.newscientist.com/article/mg20827904.600-wireless-at-the-speed-of-plasma.html`

ANNOTATION: This is a magazine article that describes some recent advances in creating plasma antennas based on silicon diodes.

[17] T. R. Anderson, *Horizontal Plasma Antenna Using Plasma Drift Currents*, Tech. Rep. 09/285.176, Office of Naval Research, Department of the Navy (1999)

ANNOTATION: This paper was written by the same person that wrote the plasma antennas book. The showed how the US Navy might use plasma antennas for communication with submarines or stealth aircraft.

[18] G. S. Hornby, A. Globus, D. S. Linden and J. D. Lohn, *Automated Antenna Design with Evolutionary Algorithms*, American Institute of Aeronautis and Astronautics (2006)

ANNOTATION: This paper from NASA described the motiviation for designing antennas using genetic algorithm. It also talked about the time requirements and results produced by said algorithm.