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<u>Term Paper: Antennas and their Applications</u>

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Abstract

The rapid advancements in technology have revolutionized lifestyles, particularly in the field of communication. The development of the antenna by Heinrich Hertz and transmission of electromagnetic waves by Guglielmo Marconi are till date considered pioneering discoveries that transformed classical electromagnetism. This paper uses Maxwell's equations to derive the conditions necessary for charges to radiate electromagnetic waves, and proceeds to discuss the structure and functions of different antennas commonly used today. It presents the principle behind the working of a half-wave dipole antenna, demonstrating the electromagnetics behind the radiation, before providing a discussion of antenna characteristic parameters. These parameters are inclusive of radiation pattern, intensity, directivity and bandwidth among others and the importance of each parameter with regard to determining its application is also deliberated. The paper then talks about the different types of antennas and the advantages conferred by one over another. Lastly, common applications of antennas in communications and broadcasting, astronomy, navigation and defense are also presented.

Introduction

James Clerk Maxwell published a set of equations in his 1865 paper – "A Dynamical Theory of the Electromagnetic Field" that revolutionized the perception of electromagnetism and earned him the title of "Father of Electromagnetic Theory". Maxwell linked and unified the then vastly dispersed concepts of electricity and magnetism, in addition to proposing his own contribution – the concept of displacement current. However, due to its unconventional and intangible nature, his theory was scrupulously criticized by many academics and his work was not recognized until post his death when his theory was experimentally verified later by Heinrich Hertz.

Maxwell believed he had discovered a contradiction to Ampere's Law, adding to it what is termed today as "Displacement Current". However, this was against the very definition of current – flow of charged particles. According to Maxwell, displacement current did not involve any charge flow, but was merely a "current" produced by Electric Fields that varied with respect to time. An immediate consequence of this was that light was an electromagnetic phenomenon – a concept that was not easily digested due to its unconventional nature at the time.

The perception changed when Heinrich Hertz showed that Maxwell's electromagnetic theory has more substance to it that previously perceived. Hertz's famous experiment in 1879 proved the existence of electromagnetic waves that traversed at the speed of light, and that light itself was one such wave. Although the ramifications of this discovery were not imminent during the time, they form the basis for a plethora of phenomena today – inclusive of radio and communication. Modern wireless communication systems are solely reliant on electromagnetic wave propagation for transfer of data over long distances.

The electromagnetic theory as presented to this point suffices to explain the behavior of charges inside devices as well as electromagnetic wave propagation, but the link between the two – i.e. the transition between the device and space requires comprehension and understanding of the phenomena of "radiation" – the subject of this paper. Radiation is achieved through "antennas" – which is a device defined by IEEE as "a means for radiating or receiving radio waves". Antennas come in different shapes and sizes, and the type most suited for an application are determined by various criteria. Often, the required characteristics may not be achievable through a single antenna, in which case a cluster (array) of antennas is used in a specific fashion so as to achieve the desirable characteristics. This is discussed in the upcoming sections.

Radiation

The fundamental idea behind the transmission of signals through space is that a transmitting device is required to supply electric current to the antenna, as a consequence of which energy can be converted from electric power to electromagnetic waves. However, not all currents are capable of radiating electromagnetic waves, and the criteria that moving charges must satisfy in order to be able to radiate are derived as follows:

For the purpose of deriving the criteria on current to support radiation, we consider a basic source of radiation - a wire carrying an electric current [1]. The current density over the cross section of a wire can be calculated as:

$$\vec{j} = \rho_v \vec{u}$$

where ρ_v is the free charge density per unit volume (C/m^3) of the material. Differentiating this expression with respect to time, the following expression is obtained:

$$\frac{\partial \vec{j}}{\partial t} = \rho_v \frac{\partial \vec{u}}{\partial t} = \rho_v \vec{a}$$

Having expressed the current density and assuming that the current-carrying wire has a uniform cross section with very small radius, the current through the wire can be estimated by using the following equation:

$$I = \int \vec{j} \cdot \overrightarrow{ds} = \rho_v u S$$

Finally, this expression is differentiated with respect to time to obtain the result:

$$\frac{\partial I}{\partial t} = \rho_v \vec{a} S$$

This expression suggests that **a current that varies with respect to time is equivalently, an accelerated charge.** Using the point form of Ohm's Law:

$$\vec{E} = \frac{\vec{j}}{\sigma}$$

We can write the differential form of the obtained expression as follows:

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\sigma}\frac{\partial \vec{j}}{\partial t} = \frac{\rho_v}{\sigma}\frac{\partial \vec{u}}{\partial t} = \frac{\rho_v}{\sigma}\vec{a}$$

This serves to illustrate that **an accelerated charge produces a varying electric current, which in turn produces a varying electric field**. Additionally, assuming the absence of convection current, Maxwell's second equation reduces to:

$$\nabla \times \vec{H} = \vec{j}$$

Equivalently,

$$\nabla \times \vec{H} = \sigma \vec{E}$$

Therefore, it becomes evident that **a time-varying current or an accelerated charge produces a varying electric field, which in turn, produces a varying magnetic field.** It is this phenomenon that time varying electric fields induce magnetic fields and vice versa, resulting in a continuous reinforcement that results in the propagation of the electromagnetic wave. The key point is the source of it all, the accelerated charge particle.

Since acceleration is a vector quantity, variation in acceleration could refer to variation in terms of magnitude, or direction or both. Therefore, directional variations include changing the direction of charge traversal, whereas magnitude variations refer to change in velocity of the charged particle. Accordingly, the criteria that charge inside a material must satisfy to achieve radiation may be summarized as follows [1]:

1. A stationary charge has no current associated with it and will therefore not radiate.
2. A charge moving with constant speed along a straight wire has no acceleration associated with it and will therefore not radiate.
3. A charge moving with constant speed along a curved, bent, or discontinuous wire, will result in the occurrence of radiation.
4. A charge that oscillates with respect to time will result in radiation even if it oscillates in a straight line.

These criteria are fairly easy to comprehend as the objective is to achieve acceleration of charged particles (electrons) inside a wire either in terms of its magnitude or its direction,

Radiation Mechanism of the Antenna

The radiation mechanism will be illustrated through the example of one of the most basic antennas – the dipole antenna. According to Christodoulou and Wahid (2001, p.21), a dipole antenna is a center-fed dipole consisting of two linear conductors that are equal in length and separated by a small gap [2].

The radiation is caused due to the continuous periodic reinforcements of electric and magnetic fields. This is mathematically evident from Maxwell's Equations [3], which are summarized as follows:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathrm{t}} \quad , \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial \mathrm{t}} \quad , \quad \nabla \cdot \mathbf{D} = \rho_v \quad , \quad \nabla \cdot \mathbf{B} = 0$$

Equation 1: Maxwell's Equations

The radiation mechanism is illustrated through the aid of a "dipole antenna". Dipole antennas are the most common form of wired antennas, and their differences with respect to other antennas are presented towards the latter part of this report. For example, the half wave dipole antenna gets its name from the fact that in order to efficiently radiate, the length of the antenna must be half the wavelength (half-wave). Furthermore, the concentration of charge during the instantaneous time corresponding to the peak of the signal resembles a dipole arrangement.

This can be understood by studying the structure of the dipole antenna. The dipole antenna consists of two wires/rods arranged in the manner as shown in the figure. It is evident that each rod is a quarter of the wavelength and thus, the length of the antenna is half the wavelength. It is also evident that in order for the antenna to radiate, the charge inside the rods must accelerate, preferably through oscillation. This is achieved through a sinusoidal input that is fed to the antenna rods through the coaxial cable depicted in the figure.

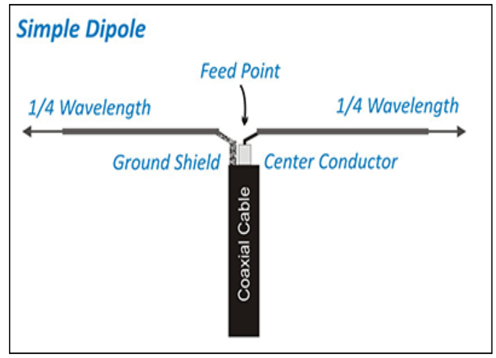

Figure 1: Half Wave Dipole Antenna [4]

The radiation mechanism can be visualized over the time period, T, of the sinusoidal source. The key point is that the currents in the rods oscillate over time, and are always in the same direction. This can be modeled by positive charges flowing in the direction of current and can be visualized as the accumulation of positive charge at the rod end in the direction of current flow, and a negative charge at the other end. Consequently, electric field lines that initiate from the positive charge and terminate at the negative charge can be used to model the electric field. According to Balanis (2005, pp. 14-15), in the first quarter cycle of the period (i.e., at $t = T/4$), the electric field lines are created around the dipole as shown in Figure 2. These wave lines exist due to the maximum value the charge density on the conductors of the antenna has reached. Moreover, at $t = \frac{T}{2}$, these waves will have traveled a distance of $\frac{\lambda}{4}$ radially outwards [1].

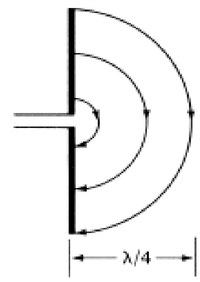

Figure 2: Electric Field at t = T/4 [1]

During the second quarter cycle of the period ($\frac{T}{4} < t < \frac{T}{2}$), the originally radiated wave lines (the first three lines) will have traveled an additional $\lambda/4$ distance and the charge density on the conductors will start to diminish as a result of the opposite current flow. Further, due to the opposite current flow, the electric field lines will be produced in the opposite direction to the previous fields, which are presented by the new three lines, and will have traveled a distance of $\lambda/4$ as shown in Figure 3. At the end of the second quarter cycle ($t = T/2$), current will reach a zero point; thus, the charge distribution is zero everywhere [1]. This makes the antenna neutral, producing a charge-free region around the antenna. This will force the previously radiated opposite field lines to make closed loops since the antenna can be considered a source-free region. The waves will have traveled a distance of $\lambda/2$ radially outwards as shown in Figure 4.

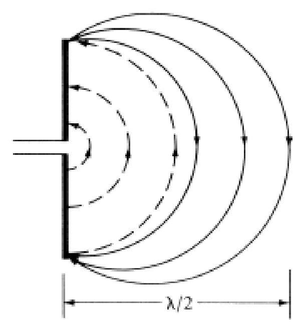

Figure 3: Electric Field at t = T/2 [1]

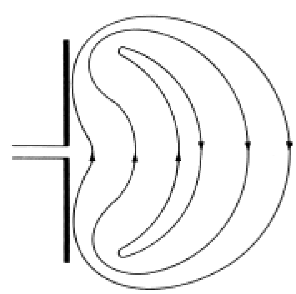

Figure 4: Full Picture at t = T/2 [1]

In the second half cycle, ($\frac{T}{2} < t < T$), the same procedure is repeated with the exception that the field lines will be opposite in direction to those of the first half cycle. This process is reiterated continuously to form electric field loops and magnetic field loops which are mutually perpendicular. This results in the wave that propagates radially outwards in space. However, the radiation is not symmetric radially as one would expect because of the constraints of reality imposed on the theoretical model. As a result, antennas have directivity and have different radiation patterns. These are some of the characteristic parameters of the antenna, which are discussed in the following section.

Characteristic Parameters of the Antenna

Antennas may be classified on the basis of various characteristic parameters. These parameters are deterministic of the application of the antenna, and vary depending on its type thereby influencing antenna performance. Some important parameters of antennas are summarized below:

Radiation Pattern

It is defined as "the graphical or mathematical representation of the antenna radiation as a function of space" [5]. It is a pattern of the radiation represented either through equations that provide the parameter intensity given the position coordinates or as is more common, the graphical representation of the same. The representation is achieved through "lobes" which are regions of the radiation pattern with relatively strong radiation intensity, and may be plotted in two or three dimensions as exemplified below:

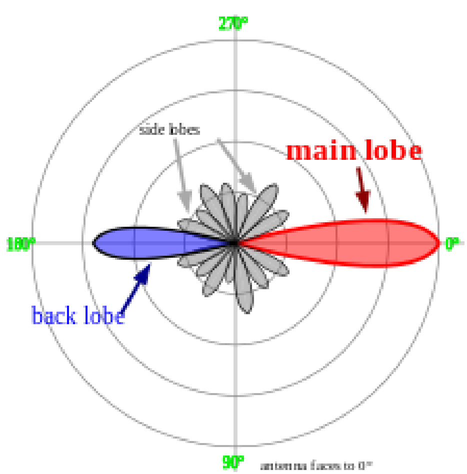

Figure 5: Two-Dimensional Radiation Pattern [6]

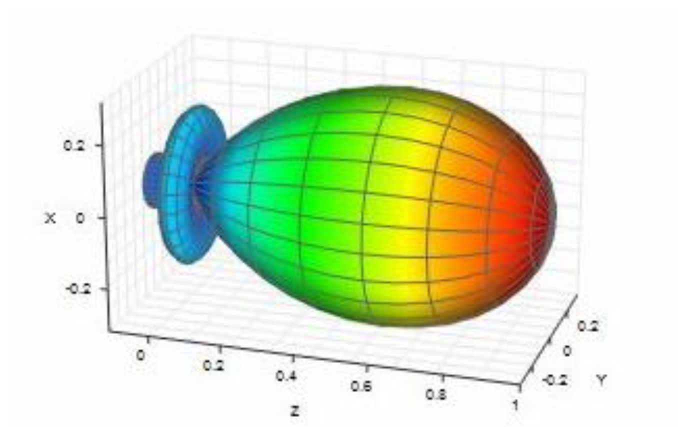

Figure 6: Three-Dimensional Radiation Pattern [7]

The main lobe contains the direction of maximum radiation and is also referred to as the major lobe. Other lobes have a differing intensity of radiation, but the amount can easily be interpreted through the graphical representation.

Radiation Intensity

The Radiation intensity is defined as the power radiated from an antenna per unit solid angle (steradian). The steradian is the solid angle at the sphere center that subtends a surface area equivalent to that of a square with side length ‘r’ [1]. This is demonstrated in the figure.

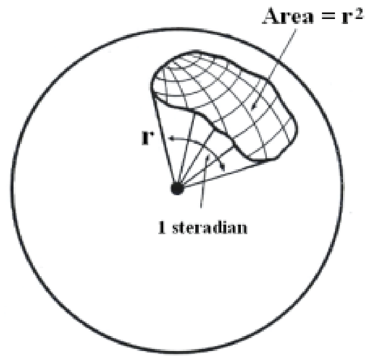

Figure 7: Steradian: The Solid Angle [8]

Radiation Intensity is a far-field parameter, and it is, therefore, more common to talk about the radiation intensity at a distance from the antenna. The characteristic is essential as it determines how strong a radiated wave is at a distance [2].

Beamwidth

Beamwidth is defined as the maximum angular separation between two points on a radiation pattern. These two points are chosen to represent meaningful quantities. The two important beamwidths are: The Half-Power Beamwidth (HPBW) and the First Null Beamwidth (FNBW).

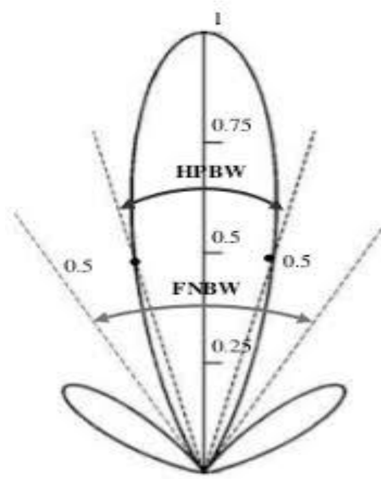

Figure 8: Beamwidth [9]

The default reference of beamwidth as accepted by the scientific community is the HPBW, which is the angular difference at which the power drops to half the peak value. It is illustrated in the figure.

Directivity and Directive Gain

Directivity refers to the antenna’s ability to concentrate its radiation power in a certain direction. An isotropic antenna is a theoretically ideal antenna, which radiates equally in all directions. Close approximations of the isotropic antenna are employed in systems where the direction vector between source and observation point is not known. However, most applications require transmission and reception in a fixed direction (such as dish antennas and satellites), and therefore, directivity comes into the picture [1][2].

The directive gain is the ratio of the intensity of radiation in a particular direction to the power had the antenna been isotropic. It is essential to understand that the antenna is a passive device, and the gain is directional alone and not in terms of power.

Bandwidth

The bandwidth of an antenna is the range of frequencies over which it can receive or transmit signals. The extent of the bandwidth is determined solely by the application: For example, receptor antennas may be required to be highly selective (less bandwidth) in order to minimize noise.

Types of Antennas

The different types of antennas in terms of their structure and geometry were designed to meet the applications they are best suited for. The focus of this section is different antenna types.

Wire Antennas

Wire antennas are extremely common and therefore familiar, and can be found in automobiles, ships, and buildings among others. Common wire antennae include the dipole antenna (long dipole and short dipole), loop antenna and helical antenna.

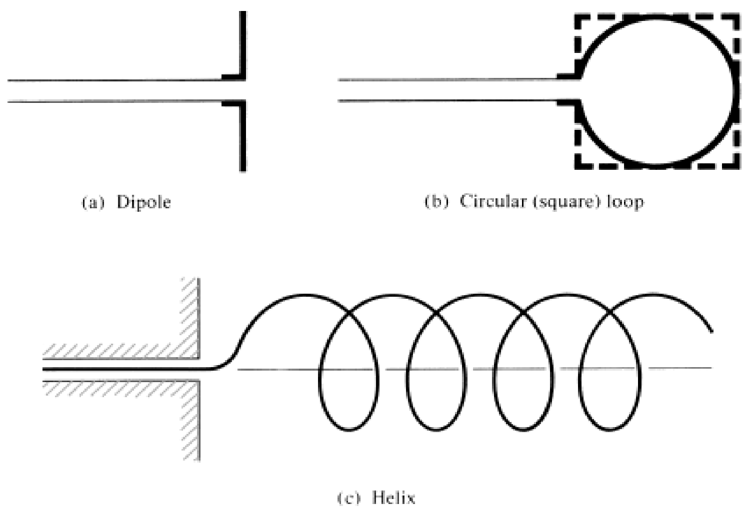

Figure 9: Wire antennas [1]

Aperture Antennas

It is evident that wire antennas can cause inconvenience if the device requiring application is compact. Often, the long antenna wire or helix may not be supported by the geometry of the device. Aperture antennas were developed to overcome this. Another advantage that they provide is the ability to withstand environmental conditions due to being covered by a dielectric. These properties are particularly useful for aircraft and spacecraft applications. Although aperture antennas can become extremely sophisticated in design when operating at higher frequencies, some simple ones are shown below:

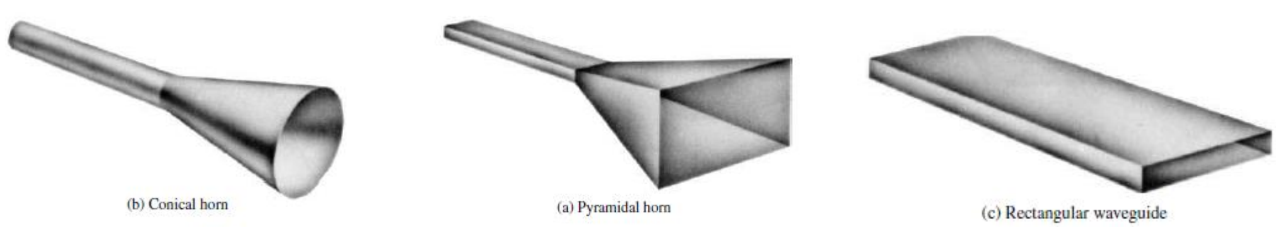

Figure 10: Aperture antennas [1]

Microstrip Antennas

Microstrip antennas are low profile antennas which are simple and inexpensive to manufacture. They are usually made up of a metallic patch (usually rectangular or circular) mounted on a grounded substrate with a dielectric material in between. The most important advantage of microstrip antennas is their small size, making them ideal for devices requiring small antennas such as mobile phones. Furthermore, since their size is small, so is the wavelength they support, and therefore, these antennas work at high-frequency ranges, usually in the Gigahertz (GHz) range. Microstrip antennas have low radiation and are also used in satellites and missiles.

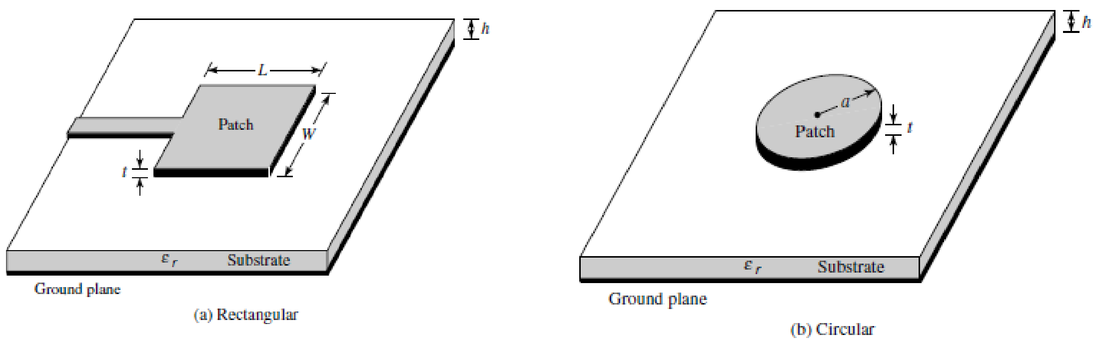

Figure 11: Microstrip Antennas [1]

Half Wave and Quarter Wave Dipole Antenna

The half wave dipole is the world's most popular antenna. It has been discussed in the former part of the paper for illustrating the radiation mechanism. The energy is radiated from the center of the antenna as the ends of the conducting rods are open circuited. The electric field radiates in a donut shaped pattern around the dipole axis, and the magnetic field radiates in a circle outward from the antenna. The quarter-wave monopole is very similar; it consists of one-half a dipole plus a perfectly conducting plane. As a consequence, most of the parameters are halved, including the total power radiated.

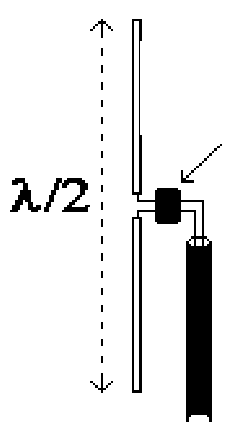

Figure 12: Half-dipole antenna [1]

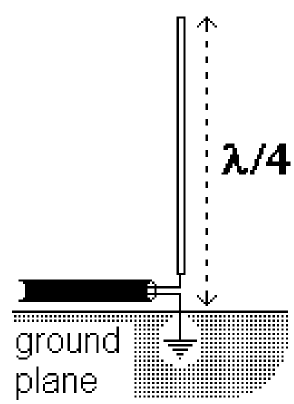

Figure 13: Quarter-dipole antenna [1]

Antenna Applications

Different types of antennas find different applications in their respective fields based on the advantages conferred by the particular type. The following section discusses three of the most important applications of antennas.

Communication

Antennas are extensively used in wireless communications, as wireless communications are reliant on the transmission and reception of electromagnetic waves for data transfer. The most common antenna used in communications is the "quarter wave whip antenna", which is a monopole antenna. This is ideal for cellular phones due to its size and structure, and operates in the 400-500 MHz. Another commonly utilized antenna in the communication sector is the "Quarter Wave Helical Antenna", which is still smaller than the whip antenna and exhibits similar performance. The mobile phone that is used extensively today relies on these antennas for transmitting and receiving signals.

Another important antenna used in communication is the retractable antenna, that is composed of two separate antennas that are electrically decoupled. This antenna functions as a whip in the extended position, and as a helical antenna when retracted. Further, tall transmitting towers used for television and radio use VHF (Very High Frequency) and UHF (Ultra High Frequency) antennas [2]. Since they are required to cover large areas in addition to meeting the frequency requirements, they are built in tall transmitting towers. VHF and UHF cover frequencies from 3MHz to 3000 MHz, and include television bands as well as AM and FM radio broadcasting bands [2].

In order to receive signals, it is possible that the characteristics of a single antenna type may not be as is required. Therefore, antennas are used in arrays to achieve the desired characteristic parameters [1]. The most well-known type of receiving antenna is called a Yagi-Uda array antenna. It is a high-gain antenna with a different size of conducting arrays that cover and receive a wide range of frequencies. However, Yagi arrays must be directed towards the transmission tower due to their high directional gain.

Figure 14: Yagi-Uda Array Antenna [10]

Astronomy

Another important field which utilizes antenna technology vastly is astronomy. Astronomical observation centers require extremely highly sensitive antennas in order to transmit and receive signals into space. This requires antennas with high radiation intensities, directivity and often bandwidth [11]. Long Helical Antennas are used to meet these requirements as they have an extremely high directional gain. This is essential as antennas receiving signals from space must be highly sensitive. Therefore, concentrating all the power of the antenna in the known direction of reception is essential. Long Helical Antennas are able to achieve this efficiently due to their structure and circular polarization [11].

Figure 15: Long Helical Antenna [12]

Navigation and Defense

Ships and Automobiles use antennas extensively for navigation and positioning. The Global Positioning System (GPS) was made possible through satellite transmission and reception of location via antennas. It is common for ships to use nearly isotropic antennas to detect signals as the position of the other party need not be known. However, ships also have directional antennas in order for radar applications. Military equipment inclusive of drones and missiles also use antennas to be able to receive instructions from the base station and be controlled accordingly [11]. It is therefore evident that the applications of antennas are diverse and extensive.

Conclusion

Maxwell's Equations eloquently unified classical electromagnetism in addition to paving the way for comprehending electromagnetic wave propagation. The link between the two is the conversion of energy from the former form to the latter or vice versa, and antennas achieve this through radiating or transmitting waves. The principle behind radiation is relatively simple and is attributed to the continuous reinforcement of electric and magnetic fields as evident from Maxwell's equations. The principle of accelerating charges to produce time varying electric fields which in turn produce time varying magnetic fields is exploited to develop different types of antennas – wire, aperture and microstrip among others. Often, the demands of a need are not fulfilled by a single antenna, which can be overcome by using arrays of antennas in order to meet the requirements. The different types find applications in diverse fields based on their size, cost, structure, and feasibility.

The suitability of an antenna for an application is determined by various characteristic parameters that classify them. These include radiation pattern, intensity, beamwidth, bandwidth, directivity, and gain. Different types of antennas are used in communication, radio and television broadcasting, astronomy, navigation, and defense. However, antennas are not limited to only these fields but find diverse and extensive use in everyday life, justifying the active global research and involvement of the scientific community in improving the efficiency of these devices.

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