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A Comprehensive Review of Antenna Technologies for Foliage Penetration Radar Systems

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Abstract: **Foliage Penetration Radar (FOPEN) systems have garnered significant attention for their ability to detect and locate targets obscured by dense vegetation. Antennas are fundamental to the performance of these systems, facilitating the detection of concealed objects in challenging environments. This paper provides a thorough review of the antenna technologies employed in FOPEN radar systems, tracing their historical evolution and highlighting their critical role. Antennas are classified based on operational requirements and system configurations, with a detailed examination of key advancements such as phased array and adaptive array technologies. These advancements are evaluated for their contributions to improving radar resolution, detection range, and adaptability to complex terrains. Additionally, the challenges in designing antennas that balance wideband capabilities, high directivity, and polarization diversity are discussed, with an emphasis on optimizing foliage penetration. The paper also explores the integration of beamforming techniques, which enhance signal-to-noise ratio and enable dynamic beam steering. Through this analysis, the study offers insights into current trends and future research directions for next-generation FOPEN radar systems.**

Keywords: **FOPEN, Antenna, Array, Gain, Bandwidth, Directivity, VHF/UHF, Ultra-Wideband (UWB), Dipoles, Substrate.**

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1. INTRODUCTION

Radar is an electromagnetic detection system that uses radio frequency(RF) waves to detect and determine targets range, angle and velocity (1), (2). Radars can be classified into various categories based on factors such as the frequency band used, the type of antenna, and the waveform applied (3), (4). Monostatic radars use the same antenna for both transmission and reception of signals or have separate antennas that are located very close to each other (5). In bistatic radars, the transmit and receive antennas are positioned at two separate geographic locations, with a considerable distance between them. Earlier the radar was only used for the military surveillance but now the they are used in used in multiple applications other than defence

such as weather monitoring, traffic control, earth mapping, person monitoring/recognition etc (6), (7), (8), (9), (10). Foliage Penetration Radar (FOPEN) systems are essential in various applications, including military surveillance and search and rescue operations. These systems are specifically designed to detect objects concealed within dense vegetation, where traditional high-frequency radar systems often fail (11). According to Bhavsar et al. these systems typically use lower frequencies in the 0.5 to 3 GHz range, as these frequencies are better at penetrating through foliage, unlike higher frequencies that are more easily absorbed (12), (13). One of the most crucial components of any radar system is the antenna, which serves as the interface between the radar transmitter and receiver. The design of the antenna determines its efficiency in recognizing and detecting the objects under the dense foliage and must effectively transmit and receive the electromagnetic waves capable of penetrating through the foliage while minimizing distortion, scattering and attenuation. This type of antennas operates using ultra-wideband signals for the higher resolution. In the RF section of the radar system, phased array antennas are commonly employed due to their ability to steer beams electronically, enabling wide-area scanning without any physical movement. These antennas are paired with a two-stage baseband amplifier that acts as a low-pass filter, ensuring only the desired low-frequency signals are processed. Devesh et al. proposed a technique to extract various waveforms corresponding the RF components of the radar varied over time (14). Received signal often consist of interference therefore, MATLAB is often used for signal processing tasks, such as updating time plots based on the captured data, with the antenna ensuring consistent signal quality (15), (16). Detecting moving targets in FOPEN systems (17), (18) presents significant challenges, as the radar must simultaneously transmit and receive signals, necessitating complex computations. To reduce system complexity, moving objects are detected by analyzing the Doppler shift in the received signal, which results from the relative movement (19) between the object and the radar system (20), (21). The doppler frequency will be positive if the target is moving closer to the radar and negative if it is moving farther away from it (22) and by using this micro Doppler signatures Akhter and Jayakumar et al. proposed a algorithm to detect LSS targets (23), (24), (25). In order to overcome the similarity between the micro-doppler signatures Haan et al. proposed the use of state-of-the-art ML techniques (26). To enhance target tracking accuracy, a Deep Convolutional Neural Network (DCNN) mechanism is employed, which aids in feature extraction and estimating the target's range and velocity, leading to more precise tracking in real-time applications (27), (28), (29), (30) . Hasan et al. studied the use of the SVM which requires very less computation in order to increase the accuracy of the CNN results. CNN based radar system has several advantages such as no lighting is required, robustness against weather conditions, day–night remote sensing, capability of atmospheric propagation, production of inconspicuous images with inherently false color, and human-privacy undisclosed detection/imaging, and so on, over the available array of other surveillance methods: vision-based sensors, thermal cameras, acoustic sensors, and infrared sensors (31), (32). Thus, nowadays, the radar-based low RCS aerial targets detection and classification gains more attention and increases rapidity. One of the application of the CNN based radar is to determine the Human Activity Recognition (HAR) which plays a critical role in national security, rescue mission and healthcare etc (33), (34).

In FOPEN radar systems,on the receiver side Electronic Support Measures (ESM) receiver is commonly used. These receivers typically include an intermediate frequency (IF) converter to limit the input signal to a specific band, an analog-to-digital converter (ADC) for digitizing the signal, and a field-programmable gate array (FPGA) (35) for implementing digital signal processing algorithms such as the Fast Fourier Transform (FFT) (36) and also facilitates the generation of complex waveforms for radar and communication systems (37). In time-frequency (TF) analysis, the time and frequency domain representation of a signal are combined into a time frequency energy density function (38), (39). However, FFT utilization can introduce latency, leading to missed samples. To address this issue, multiple FFTs are employed to increase throughput and prevent sample loss (40).

2. BACKGROUND AND IMPORTANCE

Antennas are essential to the performance and efficiency of Foliage Penetration (FOPEN) radar systems, which are designed to locate and track targets hidden by natural obstructions such as trees, shrubs, and dense foliage. Given that FOPEN systems operate at low frequencies, including VHF, UHF, L-band, and P-band, the design and capabilities of the antennas play a crucial role in determining how effectively the radar can detect objects obscured by vegetation. A key function of antennas in FOPEN systems is facilitating signal penetration through dense foliage. Antennas with a broad frequency range can enhance the penetration depth, improving the radar's ability to detect targets behind vegetation. Advanced antenna designs, like phased arrays, offer electronic beam steering, which increases detection accuracy and allows for faster scanning without relying on mechanical movement. This electronic steering significantly improves the versatility and efficiency of FOPEN radar systems by providing multi-directional scanning and flexibility in beam control (41). Additionally, antenna design is instrumental in minimizing environmental clutter caused by foliage, such as leaves and branches. Wideband antennas and dual-polarized configurations improve the radar's ability to distinguish between man-made targets and natural surroundings, thereby increasing detection accuracy. These antennas also reduce signal reflections and scattering, enhancing the signal-to-noise ratio and enabling clearer identification of targets in complex environments (42). Akhter et al. proposed the C-band photonic radar which enhances FOPEN radar systems by providing higher resolution, adaptive beamforming, and improved signal-to-noise ratio for detecting targets through dense foliage. It also enables better detection of LSS (low, slow, small) targets with real-time environmental adaptation (43).

A lot of experiments have been performed in FOPEN technology using Ultra Wide-Band (UWB), Ultra High Frequency (UHF) and Very High Frequency (VHF) bands over the past 20 years (44). Modern FOPEN radars incorporate active electronically scanned arrays (AESA), which enhance performance by providing higher gain, more effective beamforming, and multi-frequency operation. AESA technology, with its precise control over the shape and direction of beams, improves foliage penetration and target localization, making it particularly valuable in military settings where detecting concealed objects is critical (45). Raj et al. presented the design and implementation of a Frequency-Modulated Continuous-Wave (FMCW) L-Band Radar using Software-Defined Radio (SDR) and the GNU Radio framework, which is highly relevant for Foliage Penetration (FOPEN) applications. L-band frequencies (1-2 GHz) are known for their ability to penetrate dense foliage, making this design particularly suitable for detecting and tracking concealed objects in forested or cluttered environments. The use of SDR enhances flexibility and adaptability in waveform generation and processing, allowing real-time tuning for improved foliage penetration and target detection capabilities in FOPEN systems (46). As FOPEN systems continue to evolve, the role of multi-band antennas is increasingly important. These antennas enable radar systems to operate across different frequency ranges, which is critical for adapting to various environmental conditions and mission requirements. This adaptability allows FOPEN radars to maintain high performance in different foliage densities and ground clutter levels, making them versatile for a wide range of applications (47). Lastly, with the rise of adaptive beamforming and machine learning in radar technology, the design of antennas has become even more significant. Antennas that support adaptive beamforming improve the radar's ability to filter out environmental clutter and concentrate on relevant targets, further enhancing detection accuracy in dense foliage environments. Therefore, continuous advancements in antenna technology are vital for advancing FOPEN radar systems in both military and civilian sectors .

3. HISTORY OF ANTENNAS IN FOPEN RADAR SYSTEM

The evolution of antennas for Foliage Penetration Radar (FOPEN) systems has been shaped by the need to detect objects hidden by natural obstacles like trees and dense vegetation. Initial research into FOPEN radars began during the Cold War, with military applications such as spotting concealed enemy forces or equipment being a key driver. These early systems operated at low frequencies, primarily in the VHF/UHF range, to maximize their ability to penetrate dense foliage. Antennas at this time were simple, often omnidirectional or basic dipoles, prioritizing wide bandwidth and penetration depth over resolution or accuracy. A notable example is the AN/TPS-25 radar, developed in the 1970s, which employed straightforward antenna designs to achieve modest detection capability through heavy foliage (48). In the 1990s, phased array antennas were introduced to improve the performance of FOPEN systems. These antennas allowed for electronic beam steering, eliminating the need for physical movement, which led to faster scanning and enhanced image resolution. One prominent example was the Tactical Endurance Synthetic Aperture Radar (TESAR) developed by the U.S. Army, which utilized phased array technology for improved foliage penetration and surveillance. By integrating phased arrays with synthetic aperture radar (SAR) techniques (49) which performs imaging using radio frequency (RF) waves under a range of conditions and is applicable in both civilian and defense sectors (50), (51), TESAR was able to penetrate dense vegetation and produce high-resolution images of hidden objects (41). In SAR the transmit signal requires long duration to travel and therefore, the received and transmitted signals superimpose each other. To overcome this interference Sharma et al. proposed a technique in which the receiver signal uses the pulse compression techniques which makes the received signal distinguished for each and every range cells (52). Another method to overcome the antenna-based interference is effectively mitigated through array pattern shaping using array processing techniques (53). Beamforming, or array pattern shaping, is accomplished by coherently integrating spatial data samples from an array with controllable elements, a method widely employed to enhance radar performance. From the 2000s onward, FOPEN systems saw the incorporation of advanced phased array technologies like active electronically scanned arrays (AESA), which offer more precise beamforming, greater signal gain, and the ability to operate across multiple frequency bands. Research also focused on developing smaller, wideband antennas and dual-polarized phased arrays to better differentiate between natural and man-made objects behind foliage. These advancements enabled the development of more compact, mobile FOPEN systems for use in military operations, environmental monitoring, and disaster response (45). Today, FOPEN systems continue to evolve, with current research focusing on expanding the frequency range to include L-band, P-band, and VHF/UHF bands, providing varying levels of penetration and resolution based on the environment. Phased array antennas capable of operating across multiple bands are essential for modern FOPEN systems, offering versatility for different mission needs. Additionally, recent advances in adaptive beamforming and machine learning algorithms are helping to improve the radar's ability to filter out foliage-related clutter and enhance target detection accuracy .

Historically, antennas used for the FOPEN radar systems are parabolic dish antennas, characterized by a parabolic reflector that focuses electromagnetic waves into a narrow beam and allows the waves to travel great distance (54). Horn antennas, another type commonly used in FOPEN applications, feature a conical horn structure that acts as an impedance transformer between the waveguide and free space. The aperture, or open end of the horn, influences the radiation pattern and directivity. Although these antennas provide good gain and directivity but while operating at the lower frequencies the size of these antennas are very large. For ground based radar system it is very difficult to obtain gain and directivity while maintaining a considerable size. Log-periodic dipole antennas (LPDAs) have been employed (55), offering advantages such as a directive radiation pattern, linear polarization, and a low cross-polarization ratio over a wide frequency range. A LPDA consists of number of dipole elements connected through a common feed. Parameters such as length, diameter and spacing of one element are different from another element. The parameters can be calculated using the basic equations:

$$\sigma = \frac{d_n}{2L_n} \qquad (1)$$

$$L_{n+1} = L_n \times \tau \qquad (2)$$

$$X_n = h_n \times \tan(\alpha) \quad (3)$$

$$\alpha = tan^{-1}\left(\frac{1-\tau}{4\sigma}\right) \quad (4)$$

The spacing between two consecutive dipole elements are calculated using the Eq.[1], length of nth dipole is calculated using the Eq.[2] where τ is the scaling factor and distance from any dipole element to the source is calculated using the Eq.[4]. The length of the first dipole element is calculated using reference frequency.

LPDAs achieve enhanced bandwidth by increasing the number of dipole elements, with larger dipoles acting as reflectors for increased gain (56) at lower frequencies and smaller dipoles as directors for higher frequencies. Kenny et al. proposed a LPDA design which uses the pulse compression with time multiplexed waveform in which the long pulses are compressed into short pulses to detect targets within the short ranges with high resolution. To estimate the target's direction accurately amplitude centroiding is used which calculates the centroid of the amplitude of the received signals from the scanned area as the amplitude of the received signal is strongest if the beam is directed towards the target. In order to detect the moving targets from the vegetation pulsed Doppler system is used which separates the moving targets form the stationary targets but introduces detection latencies, to minimize these latencies the processor operates at the rate up to 16 times faster than the integration period (57).

Other than LPDA antennas that are used in FOPEN applications include discone antennas. Nagulpelli et al. designed a discone antenna capable of operating at UHF/VHF frequency band, with its dimensions determined by the following equations $H = 0.7\lambda$, $B_1 = 0.6\lambda$, $D = 0.4\lambda$ and $\delta \leq D$. The design of the dicone antenna is such that a conical shaped antenna is mounted on the cylindrical ground plane with a certain gap between them. The antenna is fed with a 50Ω input impedance microstrip line that connects the ground plane with the cone (58). Shinde et al. designed a dipole array antenna for FOPEN application in which unlike the conventional phased array antenna utilizes the coupling that occurred because of the tight coupling between the elements to achieve the UWB performance (59). Vivaldi antennas, known for their wide frequency range and high gain, are particularly suitable for FOPEN systems due to their ultra-wideband performance (60). Vivaldi antennas consist of a planar structure typically fabricated on a PCB with the help of a microstrip line. It features an exponentially tapered slot that transition from a narrow width from the feed point to a wider aperture at the open end that enables the gradual impedance transformation for the wideband applications. It uses a balun for the impedance matching to ensure that the antenna operates effectively without any impedance mismatching. Livington et al. proposed a design of a Vivaldi antenna in the form of the 2-D array of connected dipoles scaled to operate at lower frequencies for FOPEN applications. In this design the array is characterized in such a way that the impedance between the aperture and the free space wave is matched directly eliminating the need of long flared transition required in the conventional Vivaldi antenna. Each element is fed with a wideband balun integarted behind the ground plane (61). Furthermore for through wall detection applications Vivaldi antenna is employed with MIMO technology to enhance the detection capability (62). Phased array antennas are now the preferred choice for FOPEN radar systems due to their ability to manipulate phase for improved gain and directivity. Other antennas, such as log-periodic dipole antennas, bow-tie antennas, and microstrip patch antennas, have also been used, although they tend to increase in size and complexity at lower frequencies.

Recently numerous advancements in the antenna design has made the construction of antenna lesser complex and more cost effective. Several methods exists for effectively miniaturizing the size of an antenna, it is further classified into two categories: topology-based and material-based miniaturization technique (63). In topology based miniaturization technique the antennas are modified by changing their current density distribution, geometry and electrical dimensions which are defined on the terms of gain, radiation pattern, matching input impedance, bandwidth etc. Based on these methods an effective design can be developed to achieve the desired radiation properties while keeping the dimensions of the antenna as compact as possible. This method further divides the antennas into the ones with space filling curves. The mathematical or geometrical curves are used to make the size of the antenna small , which is implemented using either meander antennas or fractal antennas[Fractal antennas]. In the meander antenna the long straight wire is bent in a zig-zag form to occupy the shorter length. In fractal antenna the basic idea is to use irregular or fractal structures to fit a relatively longer length into a much smaller area (64). It provides the input impedance and the radiation pattern similar to that of large antennas (65). Another method used in topology based miniaturization is to make an antenna that is smaller but electrically larger. This method can be achieved in several different ways, the first method is to introduce a slot comparable to the size of its wavelength. The slot changes the return path of the current at the discontinuity by dividing the part of the current into the displacement current radiating from one edge to another and into the surrounding environment. One of the drawbacks of this approach is that the radiated signal from the embedded slot can couple and enter the adjacent electronic device and represent unwanted clutters and noises which in return if left uncontrolled may create electromagnetic compatibility issues and can also reduce the directivity by decreasing the front-to-back radiation. Another method is to use the capacitive and inductive loading to increase the propagation delay which creates a slow wave structure. Another method is to use a half wave long transmission line resonator that satisfies the two boundary conditions at its left and right terminals, these boundary conditions can be changed by using the combination of short and open circuits and other reactive loads reducing the effective size of the antenna (63).

Material-based miniaturization involves modifying the electrical and magnetic properties of the antenna. This approach includes the use of engineered substrates and metamaterials, which exhibit unique electromagnetic properties determined by their interaction with unit cells (66). These materials are particularly useful in array antennas, where element spacing is smaller than the operational wavelength. Antennas with engineered substrates, often used in microstrip designs, can be miniaturized by using substrates with high dielectric constants. However, this may reduce radiation efficiency due to dielectric loss, making it challenging to achieve impedance matching and broad bandwidth. To mitigate these issues, substrates with both magnetic and dielectric properties have been developed (67). Another way to use metamaterial in an antenna is to use Complementary Split Ring Resonator, which consists of the ring split from one or two regions with each part made up of metamaterial. to control the resonant frequency (23) (68).

Antennas operating at the UHF/VHF frequency bands are typically larger in size. Based on antenna miniaturization studies, antennas such as LPDA is modified using the fractal or meandered dipoles instead of the conventional one. Nagulpelli et al. suggested a miniaturized discone antenna by meandering the slots from the conical part which makes the antenna to resonate at the higher frequency or to use the metamaterial based SRR exhibiting negative permeability and permittvity to improve the gain and directivity. for these purposes include spiral antennas, log-periodic dipole antennas, and biconical antennas. For instance, replacing long dipoles in log-periodic antennas with fractal dipoles can reduce size while maintaining performance. Additionally, applying corrugation to the radiator and ground plane of an elliptical UWB antenna can enhance radiation pattern, bandwidth, and directivity.

One of the most promising advancements in FOPEN radar technology is the use of linear phased array antennas, which offer significant advantages over traditional single-element designs. These antennas can electronically steer the radar beam without physically moving the structure, making them particularly beneficial for FOPEN systems. This capability allows for rapid scanning of large areas and precise beamforming on specific regions of interest, significantly enhancing the radar's performance in complex environments.

Table I: Evolution of FOPEN antennas over the decades

Year/Decade	**Development**	**Description**	**Types of antenna used**
1970-1980	Early Research on FOPEN	Initial use of simple omnidirectional antennas and basic dipole designs for military applications during the Cold War. Systems like the AN/TPS-25 focused on low-frequency operation (VHF/UHF) to penetrate dense foliage.	Omnidirectional antennas, basic dipole antennas
1980-1990	Continued Refinements	Focus on improving signal penetration through foliage, with an emphasis on wide bandwidth. Antennas were designed for better range but still lacked advanced resolution and accuracy.	Basic dipole antennas, omnidirectional antennas
1990-2000	Introduction of Phased Array Antennas	Phased array technology allowed electronic beam steering, eliminating physical antenna movement. Systems like TESAR used phased arrays for enhanced foliage penetration and image resolution.	Phased array antennas
2000-2010	Integration of AESA (Active Electronically Scanned Arrays)	AESA technology introduced more precise beamforming, higher gain, and multi-band operation. Wideband and dual-polarized antennas were used to differentiate between natural and man-made objects.	AESA (Active Electronically Scanned Array), dual-polarized phased arrays, wideband antennas
2010-2020	Advanced Phased Array Systems	Research focused on developing smaller, compact, multi-band antennas and enhancing radar accuracy. Adaptive beamforming and clutter suppression became key in improving target detection.	Multi-band phased arrays, compact phased arrays
2020-Till date	Modern Innovations	Modern FOPEN systems incorporate machine learning and adaptive beamforming algorithms. Advanced phased array antennas capable of operating across multiple frequency bands provide versatility for military and civilian applications.	Advanced phased array antennas, multi-band phased arrays, AESA

4. BASIC IDEA OF ANTENNA

The RF section of a radar includes an RF source, amplifier, power divider, power amplifier, and transmit antenna in the transmitter chain, while the receiver chain consists of a receive antenna, low-noise amplifier (LNA), and mixer (69). An antenna is a specialized transducer that converts electric current into electromagnetic waves and vice versa. Antennas are primarily used for transmitting and receiving radio waves, infrared radiation, visible light, and microwaves. Antennas are typically classified as either transmitters or receivers, although most antennas can perform both functions through a transceiver. A transmitting antenna receives an electrical current from a transmitting device and generates electromagnetic waves at a specific frequency, which are radiated through the air as a medium. These waves are then received by one or more receiving antennas (70). There are various types of antennas available, including microstrip patch antennas, phased array antennas, log-periodic dipole antennas, Yagi-Uda antennas, biconical antennas, horn antennas and reflector antennas

4.1 Antenna Characteristics

Antenna characteristics are critical parameters that describe an antenna's performance and are essential to understand before designing an antenna for a specific application. Understanding these characteristics is vital to ensure the antenna meets the desired requirements (71) (72). The key characteristics include:

4.1.1 Radiation Pattern

The radiation pattern of an antenna is a graphical representation that illustrates how the antenna radiates energy into space. It can be categorized into two types: directional and omnidirectional (31). Radiation pattern contains various lobes which are subclassified as main, side and back lobes. A radiation lobe represents the direction in which the antenna radiates effectively. A major lobe defines the direction of maximum radiation, side lobe define the radiation in an unwanted direction and the back lobes define the radiation whose axis makes the angle of 180° with respect to the antenna beam.

4.1.2 Directivity

Directivity is defined as the ratio of the radiation intensity in a specific direction from the antenna to the average radiation intensity over all directions. Directivity = $\frac{4\pi U}{P_{rad}}$, where U is the radiation intensity. When the direction is not specified, then it is referred to as maximum directivity

$$D_{max} = \frac{4\pi\, U_{max}}{P_{rad}}$$

For the isotropic source , the U and U_{max} are equal to each other. For antennas with orthogonal polarization components is referred to as partial directivity which is defined as the ratio of the radiation intensity for the given polarization in the given direction to the radiation intensity averaged over all the directions. The total directivity is given by the sum of the directivity for any two orthogonal polarizations.

$$D_o = \frac{4\pi\, U_\theta}{(P_{rad})_\theta + (P_{rad})_\phi} + \frac{4\pi\, U_\phi}{(P_{rad})_\theta + (P_{rad})_\phi},$$

where U_θ means radiation intensity in given direction in θ field component, $U_\phi$means radiation intensity in given direction in ϕ field component, $(P_{rad})_\theta$ means radiated power in all directions contained in θ field component and $(P_{rad})_\phi$ means radiated power in all directions contained in ϕ field component

4.1.3 Antenna Efficiency

This parameter evaluates the ratio of the power radiated by the antenna to the total power input, incorporating considerations of reflection, conduction, and dielectric losses. Since conduction and dielectric losses are challenging to quantify separately, they are usually aggregated into a single combined value.

$$e_o = e_r e_{cd},$$

where e_o means Total efficiency, e_r means Reflection efficiency and e_{cd} means Conduction efficiency.

4.1.4 Gain

The ratio of the intensity in a specific direction to the intensity that would be achieved if the accepted power were radiated isotropically. In most of the cases we prefer relative gain which is defined as the ratio of power gain in the given direction to the power gain of the referenced antenna in the referenced direction.

$Gain = \frac{4\pi U_{eff}}{P_{in}}$, where $P_{rad} = e_{cd} P_{in}$

By using radiated power equation, we can write

$$G(\theta, \phi) = e_{cd}[\frac{4\pi\, U(\theta,\phi)}{P_{rad}}]$$

$G(\theta, \phi) = e_{cd} D(\theta, \phi)$

When an antenna is connected with a transmission line it introduces reflection loss. So, the absolute gain is be given by

$G_{abs} = e_r e_{cd} D(\theta, \phi) = e_o D(\theta, \phi)$

When the transmission line is perfectly matched with the antenna, then the input and characteristic impedance are equal to each other, therefore $G = G_{abs}$. As discussed in directivity the gain is also associated with a specific polarization—i.e., the gain relative to one of the orthogonal components—differs from the overall gain, it is referred to as Partial Gain. The partial gain of an antenna for a given polarization is defined as the ratio of the radiation intensity corresponding to that polarization to the total radiation intensity that would be achieved if the power were radiated isotropically. Consequently, the total gain is the sum of the gains measured for any two orthogonal polarizations.

$G_o = G_\theta + G_\phi$ where G_θ and G_ϕ are given by

$G_\theta = \frac{4\pi U_\theta}{P_{in}}$ and $G_\phi = \frac{4\pi U_\phi}{P_{in}}$

Although gain and directivity of the antenna are closely related to each other, gain of an antenna takes into account both the antenna efficiency and directional properties unlike the directivity which only describes the directional properties. For getting the clear image of gain and directivity, the following cases need to be considered:

For an ideal antenna,

$$G = D$$

For lossy antenna with no reflection loss

$G = e_{cd} D$

For lossy antenna with reflection loss

$G = e_{cd}(1 - |\Gamma|^2) D$

4.1.5 VSWR

The Voltage Standing Wave Ratio (VSWR) quantifies the degree to which an antenna is impedance-matched to the transmission line. Poor impedance matching results in partial reflection of the incident wave back toward the source. The interaction between these reflections and the incident wave leads to regions of constructive and destructive interference. VSWR is determined by the ratio of the maximum to minimum voltage levels along the transmission line resulting from these variations.

$VSWR = \frac{V_{max}}{V_{min}}$

The relation of the VSWR with the voltage reflection coefficient is given by

VSWR=$\frac{1+\Gamma}{1-\Gamma}$,

where Γ is a reflection coefficient given by

$\Gamma = \frac{Z_{in} - Z_c}{Z_{in} + Z_c}$

4.1.6 Return Loss

It is defined as the ratio of the power reflected by the antenna to the total power supplied to the antenna. This ratio measures the power lost due to internal reflections within the antenna.

$RL = -20 log_{10} |\Gamma|$

4.1.7 Impedance

In an antenna, impedance is defined as the opposition to the flow of alternating current (AC) at a specific frequency. It is a complex quantity comprising a real part and an imaginary part. The real part, known as resistance, represents the real power dissipated by the antenna. The imaginary part, known as reactance, represents the energy stored in the antenna's near field.

$Z_A = R_A + jX_A$

4.1.8 Bandwidth

Bandwidth is a range of frequency over which the antenna can perform effectively. The bandwidth of an antenna cannot be properly characterized as the characteristics of the antenna vary for different applications for example when the size of the antenna is very small as compared to its wavelength, the bandwidth become insensitive to the frequency change due to their non-resonant characteristics and the dominance of reactance over resonance effects in such case the bandwidth is formulated in the terms of impedance, but when the antennas are in arrays having large dimensions as compared to its wavelength then the bandwidth is expressed in the terms of beamwidth . In order to improve the bandwidth of an MPA is to create several resonant structures into one antenna by adding more layers, more patches or more extra components (32).

For broadband antennas:

Bandwidth = $\frac{f_H}{f_L}$

For narrowband antennas:

Bandwidth = $\frac{f_H - f_L}{f_c}$

4.1.9 Polarization

Polarization describes the orientation of the electric field vector in a radiated electromagnetic wave. Understanding this characteristic is crucial in antenna studies, as it determines how effectively the antenna can transmit and receive signals. Polarization can be linear, circular, or elliptical. In linear polarization, the electric field vector remains within a constant plane. In circular polarization, the electric field rotates in a circular manner as the electromagnetic wave propagates. Elliptical polarization occurs when the electric field vector traces an elliptical path, combining aspects of both linear and circular polarization.

5. CLASSIFICATION OF ANTENNAS

Antennas exhibit a diverse array of characteristics that allow for classification based on various design principles, operational modes, antenna parameters, and, crucially, their specialized applications. For the FOPEN application antennas are classified based on their operating frequency range. The types of used at the UHF/VHF frequency band for FOPEN radar system are:

5.1 Log Periodic Dipole Antenna

For ground-based radar systems it is very difficult to obtain gain and directivity while maintaining a considerable size therefore. Log-periodic dipole antennas (LPDAs) have been employed (14), offering advantages such as a directive radiation pattern, linear polarization, and a low cross-polarization ratio over a wide frequency range. A LPDA consists of a number of dipole elements whose length and spacing increases logarithmically along the antenna axis and are connected through a common feed. This distinctive configuration allows the LPDA to maintain consistent performance over a wide spectrum of frequencies, making it ideal for wideband applications such as FOPEN radar, where effective penetration through foliage is essential. The directional radiation pattern of LPDAs facilitates their capability to penetrate dense vegetation and detect hidden targets, providing clear advantages over traditional narrow band antennas. Parameters such as length, diameter and spacing of one dipole are different from another dipole. The parameters can be calculated using the basic equations:

$$\sigma = \frac{d_n}{2L_n} \qquad (1)$$

$$L_{n+1} = L_n \times \tau \qquad (2)$$

$$X_n = h_n \times tan\, tan\, (\alpha) \qquad (3)$$

$$\alpha = tan^{-1}\left(\frac{1-\tau}{4\sigma}\right) \qquad (4)$$

The spacing between two consecutive dipole elements are calculated using the Eq.[1], length of nth dipole is calculated using the Eq.[2] where τ is the scaling factor and distance from any dipole element to the source is calculated using the Eq.[4]. The length of the first dipole element is calculated using reference frequency. LPDAs achieve enhanced bandwidth by increasing the number of dipole elements, with larger dipoles acting as reflectors for increased gain (15) at lower frequencies and smaller dipoles as directors for higher frequencies. Due to the restriction of space in the radar system the miniaturization of LPDA is very critical. The size of the LPDA can be minimized by using meandered lines or fractal dipoles which require less space than the usual dipoles or by using T- shaped top loading technique. Using the meandered or top loading techniques deteriorates the overall gain of the antenna to overcome this problem Shin et al. proposed the Folded Planer Helix dipole elements instead of the usual dipole elements. In a folded dipole, where the top and bottom parts of each dipole are electrically connected, the radiation resistance can be expressed as$R_{rad} = N^2 R_d$, , $R_d$is the radiation resistance of a single dipole arm and N represents the number of folded arms. This approach allows for easy tuning of the input resistance in electrically small antennas. However, for planar structures, N is generally limited to two. To address this limitation, FPH was developed in which When the current distribution across the arms of a folded dipole is unequal, the transformation ratio can deviate from $N^2$by adjusting the current magnitude ratio between the arms. This implies that the ratio is modified to enhance the radiation resistance of the dipole beyond the N^2 factor (73).

5.2 Discone Antenna

The discone antenna remains a preferred option for FOPEN radar systems due to its wide bandwidth and omnidirectional radiation pattern. These features are vital for radar systems operating across various frequency ranges, especially in environments with dense foliage, where effective signal penetration is crucial. Its broad frequency coverage ensures reliable target detection and better adaptability in complex terrains, making it an efficient choice for FOPEN applications requiring consistent performance in challenging conditions. A discone antenna comprises a flat disc on top and a cone-shaped structure at the bottom, which contributes to its wide impedance bandwidth. This design enables the antenna to function efficiently in UHF (Ultra High Frequency) and VHF (Very High Frequency) ranges, which are commonly used in FOPEN radar systems.

Table II: Parameters of discone antenna

Parameter	**Value**
Height	0.7λ
Base Diameter	0.6λ
Disc-cone Gap	$<=0.4\lambda$

Recent advancements have focused on improving the bandwidth and efficiency of discone antennas. For instance, Nagulpelli et al. (2018) developed a wideband discone antenna specifically for FOPEN radar, enhancing its performance in terms of bandwidth and minimizing signal distortion during foliage penetration (74). This design is ideal for FOPEN radar, where accurate detection through vegetation is critical. Similarly, Chen et al. (2011) presented a wideband VHF/UHF discone-based antenna, further improving its performance across these frequency ranges (75). Kim et al. (2005) proposed an ultra-wideband double discone antenna with tapered cylindrical wires, which demonstrated substantial improvements in both bandwidth and radiation efficiency (76). This design is especially beneficial for radar systems requiring enhanced signal reception in complex environments. The broad frequency capabilities of discone antennas make them well-suited for FOPEN radar systems, enabling effective detection of objects concealed by dense vegetation. Their omnidirectional radiation pattern ensures comprehensive coverage, vital for identifying targets in various directions. Regarding size and mobility, Ziolkowski (2008) introduced an electrically small antenna design that functions efficiently in both VHF and UHF bands, proving essential for portable FOPEN radar systems. These compact antennas maintain high performance while minimizing size, making them ideal for mobile applications where portability and efficiency are key (77). Compared to other antennas used in FOPEN radar, such as spiral and log-periodic antennas, the discone antenna offers a combination of simplicity, wide bandwidth, and ease of deployment. Its omnidirectional coverage is a distinct advantage over more directional antennas like log-periodic designs, which may require precise alignment.

5.3 Vivaldi Antenna

Vivaldi antenna belongs to the category of end-fire traveling antennas. The Vivaldi antenna incorporates a slot line design where the edge separation extends beyond $\frac{X}{2}$, with X representing the length parameter. It consists of a radiating plane and a ground plane positioned opposite each other, separated by a substrate. To achieve the desired gain, the phase velocity of the bound wave must match or exceed that of the surrounding medium, necessitating continuous phase compensation in the traveling wave structure. For maintaining a consistent beamwidth, the antenna's shape is defined in terms of a dimensionless wavelength. Different portions of vivaldi antenna radiate at different frequencies depending on their size. Another notable characteristic of the Vivaldi antenna is its ability to maintain a constant beamwidth across different frequencies, which is highly dependent on precise antenna design. In designing a Vivaldi antenna for low frequency operations, two critical factors must be considered: the transition in the feeding structure and the specific dimensions and shape of the antenna, which are essential to achieve a focused beamwidth. For the power transfer between the source and the antenna is done with a feed line. There are various feeding techniques for the vivaldi antennas such as direct feeding technique where the antenna is fed directly with a coaxial or microstrip feed line without any complex transition, coplanar waveguide feeding technique in which central conductor is flanked by two ground planes on the same side of the substrate, offering integration of the antenna with the power source and reduced radiation loss and another feeding method is to use microstrip to slotline feeding in which the transition of from the microstrip line to the slot cut on the ground plane of the antenna modifies the current distribution between them (78). To enhance gain, Panday et al. introduced two key modifications to the conventional Vivaldi antenna design. First, rectangular slots were incorporated along the edges of the exponential taper to focus the antenna's energy toward the main radiating area, thereby improving signal strength in the desired direction. Second, three thin metal strips were placed along the antenna's radiation axis, functioning similarly to the directors of a Yagi-Uda antenna, to further direct and concentrate the radiated signal for improved performance (79). FOPEN radar systems require antennas operating at lower frequency bands, which results in larger antenna sizes due to longer wavelengths. Zheng et al. addressed this challenge by designing a Vivaldi antenna utilizing magneto-dielectric ferrite material, which exhibits both high permittivity and permeability across a wide frequency range. This reduces the effective electromagnetic wavelength, thereby decreasing the antenna size. Additionally, the high magnetic loss properties of the ferrite material effectively suppress higher-order harmonics, further enhancing the antenna's performance (80). Another approach to reduce the size of the antenna involves incorporating a pair of resonant cavities, which trap electromagnetic waves at specific frequencies, amplifying them by reflecting the waves back and forth within the cavity. This method reduces the size of the Vivaldi antenna by effectively lengthening the current path (81).

Table III: Vivaldi Antennas in FOPEN Radar

Parameter	Description	Impact on FOPEN Radar
Frequency Range	Covers VHF (30 MHz – 300 MHz) and UHF (300 MHz – 3 GHz)	Essential for penetrating dense foliage and maintaining signal strength across varied environments.
Bandwidth	Ultra-wideband operation (up to several GHz)	Provides flexibility for radar to switch between different frequencies to optimize detection.

Radiation Pattern	High directivity, narrow beamwidth	Focuses radar signals in specific directions, minimizing clutter and enhancing target detection.
Gain	Varies with design; typically high due to tapering structure	Increases the range and sensitivity of radar detection, particularly in dense environments.
Antenna Size	Compact size, can be optimized for portability	Allows integration into mobile radar systems for field operations.
Polarization	Linear or dual-polarized designs available	Enhances detection capability by reducing interference and improving clutter rejection.

5.4 Microstrip Patch Antenna

Antennas designed for radar communications must be cost-effective, lightweight, and easy to fabricate. In this regard, the microstrip patch antenna has emerged as a highly successful and innovative technology in antenna design. These antennas also integrate effectively with solid-state devices such as amplifiers, attenuators, switches, and mixers. Microstrip antennas can support an infinite number of resonant modes, with the resonant frequency of each mode influenced by parameters including the patch dimensions, shape, relative dielectric constant (εr), and to some extent, the substrate thickness (h). For example, in a rectangular patch configuration, the resonant frequencies are determined by these parameters.

$$F = \frac{C}{2\pi\sqrt{\varepsilon_r}}[(\frac{m\pi}{L})^2 + (\frac{n\pi}{W})^2]$$

(82).A microstrip patch antenna comprises a metal patch mounted on a dielectric substrate, which is then placed on a ground plane. Its operation depends on the fringing effect occurring at the edges of the patch and the ground plane. To enhance the performance of the microstrip patch antenna, the fringing effect can be intensified by reducing the dielectric constant, increasing the substrate height, or enlarging the patch dimensions. The patch length and width are denoted as L and

W respectively. Due to the finite dimensions of the patch, fringing effects occur along its edges. To account for these effects and the wave propagation characteristics, an effective dielectric constant (ϵ_{eff}) is used. The patch length is effectively extended by a distance ΔL due to the fringing fields, resulting in an overall length increase of 2ΔL. This section includes the formulas necessary for designing a microstrip patch antenna. The width calculation is provided by:

$$W = \frac{c}{2f_o\sqrt{\frac{\epsilon_R+1}{2}}}, \qquad (1)$$

where c is the Speed of the light, f_o is the Resonant frequency = $1750MHz$ and ϵ_R is the Relative permittivity

Calculation of the effective dielectric constant is given by:

$$\epsilon_{eff} = \frac{\epsilon_R+1}{2} + \frac{\epsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12(\frac{h}{W})}}\right] \qquad (2)$$

Calculation of the length extension is given by:

$$\Delta L = 0.412\frac{(\epsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \qquad (3)$$

The actual length of the patch is calculated as:

$$L = \frac{1}{2f_r\sqrt{\epsilon_{eff}}\sqrt{\mu_o\epsilon_o}} - 2\Delta L \qquad (4)$$

For the width of the feed line the lower characteristic impedance requires wider feedline and the higher characteristic impedance requires narrow feedline. The width of the feedline is given by (86):

For narrow lines (W/h < 1):

$$Z_o = \frac{60}{\sqrt{\epsilon_r}} ln(\frac{8h}{W} + \frac{W}{4h}) \qquad (5)$$

For wider lines (W/h > 1):

$$Z_o = \frac{120\pi}{\sqrt{\epsilon_r}(\frac{W}{h}+1.393+0.667ln(\frac{W}{h}+1.444))} \qquad (6)$$

Using the above equations the width of the feedlines were calculated as:

W_{f1} = 3.08mm (For Z_0 = 50 ohms)

W_{f2} = 1.64mm (For Z_0 = 70.71 ohms)

W_{f3} = 0.7mm (For Z_0 = 100 ohms)

In order meet the requirements for radar and mobile communication applications, the overall size of the microstrip antenna must be reduced. By incorporating slots into the patch, the antenna's size for a specific frequency can be minimized, while also improving reliability by allowing it to resonate at lower frequencies. (87). Alternatively, the patch size can be reduced by using high-permittivity dielectrics. To detect the target concealed under the foliage, a microstrip linear patch array antenna is used (88) (89). A linear microstrip patch array antenna is a row of identical patches arranged linearly on the substrate utilizing a corporate feed network which ensures equal power distribution and consistent phase alignment for all the eight radiating elements and provides better gain and directivity (90)(42). However, the reduction of the microstrip antenna is a very challenging issue as it reduces the gain and bandwidth of the antenna. Various techniques have been proposed to address this issue, including reshaping the antenna and adding slots, employing high dielectric materials, shorting and folding the antenna, and incorporating metamaterials but due to the reduction techniques the spacing between the antenna elements is decreased which causes the mutual coupling which in turn degrades the overall performance of the microstrip antenna. In order to suppress the mutual coupling, the ground plane characteristics are disturbed in terms of size and shape (91) (92), Another method is to make some holes on the ground plane to stop some EM waves to pass through them, but this method causes the loss in antenna gain (93) (94). Alternatively, by introducing air slits on the ground plane of the patch or the parallel coupled resonator (PCR) as proposed in (95) causes a significant reduction in the mutual coupling.

RT Duroid 5880 is an ideal substrate for a patch antenna in a FOPEN radar system. It provides a favorable balance of low dielectric constant, low loss, and good mechanical and thermal stability, making it suitable for a wideband, high-frequency antenna array with minimal signal degradation across the operating band (96) (97). Beam correction methods can be employed to enhance the accuracy of the radiation pattern, concentrating the beam in the desired direction (98) (99). The ground plane is modified, both above and below the substrate, to enhance gain or shape the radiation patterns.. It is shown that the ground plane effects are significant and a wide range of radiation pattern shapes can be generated (100). One commonly used technique to enhance gain and bandwidth is the dual-feed method, which involves placing two rectangular patches on a single substrate (101) (102). This configuration allows each patch to utilize dual-feed settings, enabling the antenna to operate effectively within its designated system. The dual-feed arrangement facilitates both vertical and horizontal modes, which can lead to a degradation in polarization but ultimately helps improve impedance and gain for the antenna. Microstrip antennas can be integrated with phase shifters and matching networks using various feeding methods. Common microstrip feed methods include microstrip line, coaxial probe, aperture coupling, and proximity coupling. The microstrip line and coaxial feed methods are direct contact feeding methods that is the feed line is in the direct contact with ground and the substrate, while aperture and proximity coupling are non-contact feeding methods in which the link between the ground and substrate is given by a slot and there is no direct contact between them, but a proper care is required while feeding the patch antenna and it should be matched properly with the transmitting and the receiving antenna for better efficiency, the impedance matching in patch antenna is increased by either by using the probe-fed method (103)or by using the parallel plate radial microstrip line proposed in (104) to get rid of the challenges posed by the use of the thick probe. In the microstrip feed line method, the patch is connected to a microstrip feed line, which is a conducting strip significantly narrower than the patch. This method is advantageous due to its ease of fabrication and simplicity in matching by controlling the inset (105) (106). An increase in the thickness of the substrate also leads to the increases spurious waves which disrupts the bandwidth of the antenna.

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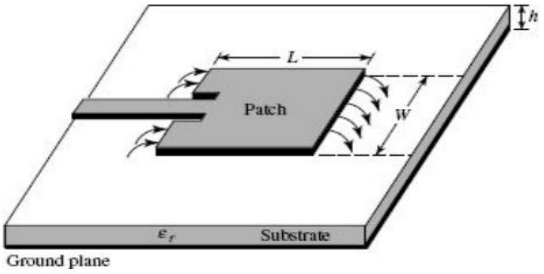

Fig. 1: Microstrip Line

In the coaxial probe feeding technique, the inner conductor of the coaxial cable is connected to the radiating patch of the microstrip antenna, whereas the outer conductor is connected to the ground plane. This configuration places the feeding point inside the patch rather than at its edge, which improves impedance matching. The coaxial probe feeding method is advantageous due to its low spurious radiation, which contributes to a better radiation pattern. A schematic representation of the coaxial probe connection to the microstrip patch is shown in Figure 2 (107). The main disadvantage of this feeding method is that it requires drilling a hole in the substrate, and the presence of the coaxial connector on the ground plane complicates the antenna's planar shape.

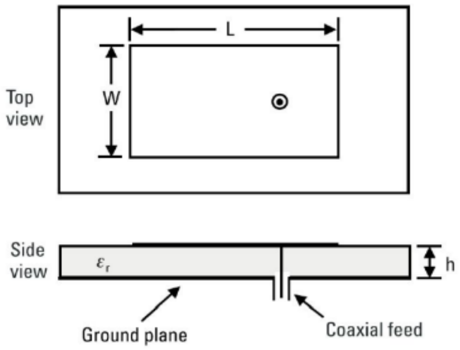

Fig. 2: Coaxial feed line

Broader bandwidth requires the use of thicker substrates, which has many drawbacks in microstrip line and coaxial feed techniques. To overcome these disadvantages, non-contact feed approaches such as aperture-coupled and proximity-coupled methods are preferred. In the aperture coupling method, as illustrated in Figure 3, The feed line is placed on a distinct layer from the patch, with the two layers separated by a ground plane. A slot is introduced into the ground plane, allowing electromagnetic energy to be transferred to the patch through this aperture. By adjusting the size of the slot such as its length and the width , the coupling is optimized to achieve the wider bandwidths. This method offers excellent isolation between the feed network and the radiating elements, as well as the ability to independently optimize the patch and feed line designs. Furthermore the overall efficiency of the antenna is enhanced by the selecting the substrates with different permittivity for the antenna and the feed line.

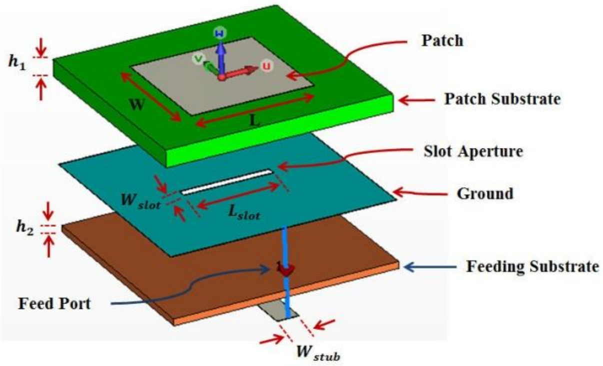

Fig. 3: Aperture-coupled feed line

In proximity coupling, as depicted in Figure 4, the feed line is located on a separate substrate layer in close proximity to the patch. Electromagnetic energy is transferred to the patch through the electric field coupling between the two layers, without direct physical contact. Furthermore, this approach allows for the use of different dielectric materials for the patch and feed line, which optimize their individual performances. This method is very useful for minimizing harmonic radiation in microstrip patch antennas built on multilayer substrates. The design tries to suppress resonances at the second and third harmonic frequencies in order to reduce spurious radiation induced by related patch modes and avoid harmonic signal emission from non-linear devices during the amplification stage. The study found that altering the length of the feeding line successfully controls the resonance at the second harmonic, while a compact resonator is used to suppress the third harmonic frequency. The connection of the feed line to the microstrip patch is illustrated in Figure 4.

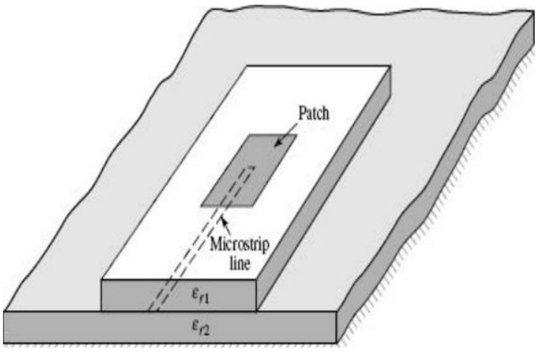

Fig. 4: Proximity Feed Line

Another method to feed the microstrip antenna is the series feed network, where the feed line passes through each patch element, with each element receiving some power. The length of the transmission line between each element produces a phase shift.

Table IV: Comparison of different feeding techniques

Parameters	Microstrip line	Coaxial	Aperture-coupled	Proximity-coupled
Ease of fabrication	Basic	Basic	Complex	Complex
Impedance matching	Basic	Basic	complex	Complex
Spurious Radiation	High	Low	Low	Low
Modeling	Basic	Complex	Basic	Basic
Bandwidth	Narrow	Narrow	Narrow	High

This method is commonly used for planar array antennas and offers a compact design with low power loss due to fewer components. However, controlling the power distribution ratio can be challenging, particularly as the number of elements increases, which may lead to imbalances due to the narrow width of the feedline. In contrast, the corporate feed network distributes power equally among each element through branching transmission lines. This method often involves power dividers or quarter-wave transformers to ensure equal power distribution. The corporate feed network provides good impedance matching and effective control over phase and amplitude for better beam formation. However, increased feed line length can lead to gain loss, which is a limitation of this method (108).

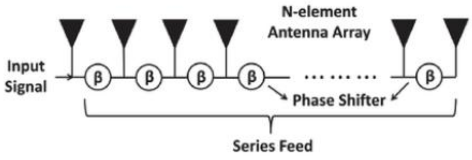

Fig. 5: Series feed Network

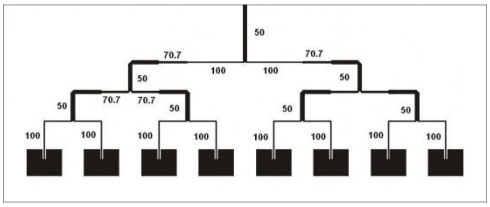

Fig. 6: Corporate feed network

Table V: Sizes of Different FOPEN Antennas in the Lower Frequency Band

Antenna Type	**Frequency Range (MHz)**	**Physical Size (Approx.)**	**Antenna Dimensions (Length × Width × Height)**	**Characteristics**
Vivaldi Antenna	500 – 3000	Medium to Large	30 cm × 10 cm × 2 cm	Ultra-wideband, high directivity, good for dense foliage penetration.
Discone Antenna	500 – 2500	Medium	40 cm × 40 cm × 35 cm	Omnidirectional, wide bandwidth, good for mobile platforms.
Log-Periodic Antenna	600 – 3000	Large	80 cm × 60 cm × 30 cm	High gain, directional, suitable for long-range detection.
Dipole Antenna	500 – 2000	Small to Medium	25 cm × 2 cm (per element)	Simple, narrowband, typically used for specific frequency bands.
Patch Antenna	800 – 3000	Small	10 cm × 10 cm × 0.5 cm	Compact, suitable for high-frequency applications, typically narrowband.
Horn Antenna	700 – 3000	Medium to Large	25 cm × 25 cm × 20 cm	High directivity, typically used in airborne or mounted radar systems.
Yagi-Uda Antenna	500 – 1500	Large	100 cm × 50 cm × 20 cm	Highly directional, narrow bandwidth, good for fixed radar systems.
Spiral Antenna	1000 – 3000	Small	15 cm × 15 cm × 1 cm	Wideband, circular polarization, good for omnidirectional coverage.

5.5 Phased Array Antenna

A phased array antenna is an antenna array capable of electronic beam steering, enabling the adjustment of signal shape and direction without requiring any physical movement of the antenna structure.. The phase difference between the signals is responsible for electronic steering (109). The array factor is crucial for determining the performance of an array antenna. It encompasses the number of elements, their relative input signals, geometric arrangement, and the resulting electric field radiation (19). When the array of antenna elements is compared with the single element antenna it is observed that there is significant decrease in the return loss for array antenna, which can be rectified with the usage of modified power dividers and with the improvement in the return loss the gain can be further increased (110). Increasing the number of antenna elements enhances beam steering capabilities. For an array antenna, the selection of inter-element spacing depends on both the wavelength of the signal and the maximum steering angle requirements (111).To accurately locate targets, elements located at the periphery typically have lower gain compared to those at the center. This technique is known as adaptive beamforming. By dividing the array into sub arrays reduces the number of channels and by using adaptive beamforming in each subarray makes the system cost efficient (112). The radiation pattern of an array antenna typically has two grating lobes that indicate the gain and directivity of the antenna. These lobes can be made sharper by adjusting the phase and gain of each antenna element. To enhance the overall efficiency of an array antenna, Genetic Algorithms (GAs) are employed to optimize the coverage area. According to Martone et al. GA’s are optimization techniques inspired by Darwin's theory of evolution, where solutions evolve through processes of crossover and mutation, referred to as generations, with each solution termed a chromosome. The fitness of each solution is evaluated using a predefined fitness function (113). In Foliage Penetration Radar (FOPEN) systems, GAs optimize radar pulse design and manage radar site configurations. They are crucial for identifying the required waveform (114). The radar system utilizes the directionality provided by the antenna elements to precisely locate the target. Mohan et al. proposed that GAs helps to reduce the size of large array antennas and minimize side lobes (115). Genetic algorithms, in integration with the Schelkunoff synthesis method, are employed to optimize the design of uniformly spaced linear and planar arrays. The objective is to determine the optimal excitation amplitudes and phases that provide a close match between the desired and calculated radiation patterns. (116). Operation of phased array antennas is based on constructive and destructive interference of electromagnetic waves. By adjusting the phase of signals, the beam can be steered in a specific direction. The phased array consists of multiple emitters, which enable electronic beam steering and beamforming where the number of emitters ranges from a few to thousands. Constructive interference occurs when signals are in phase, resulting in intense radiation in a specific direction and the phase differences between signals are controlled by delays between the emitters, and the beam intensity outside the main beam is minimal, consisting of side lobes (117). To achieve effective impedance matching between the antenna and the feed line, a balun (balanced-to-unbalanced transformer) is employed to equalize the impedance between the two, ensuring efficient signal transfer and minimizing reflections.The balun's length depends on the minimum operating frequency and maximum tolerable reflection coefficient. Constructing a balun transformer can be achieved by expanding or opening a slot aperture in the feed line, transforming it into two open transmission lines. This allows the electromagnetic field within the feeder to transition into an open space in a twin conductor line, ensuring an ideal impedance match between the feeder and antenna (118). Phased array antennas are categorized into linear arrays, planar arrays, and frequency scanning arrays. In a linear array, the elements are aligned along a straight line with a single phase shifter, enabling beam steering in a single plane. Planar arrays, on the other hand, utilize phase shifters arranged in a matrix configuration, allowing beam steering in two planes for enhanced directional control.. Frequency scanning arrays achieve beam steering by controlling the frequency, eliminating the need for phase shifters. Recent advancements in phased array technology (119) have led to the development of various configurations utilizing both passive and active phase shifters. These configurations include passive phased arrays, where a single phase shifter is employed for all array elements, and active phased arrays, which feature individual amplifiers for each element to enhance performance and flexibility. Additionally, subarray digital phased arrays are designed to control multiple beams over a limited area, while element-level digital phased arrays offer cost-efficient solutions by digitizing signals at each individual element level. Phased array antennas offer several advantages over other types, including higher total power due to the summation of individual signal powers. The beam shape can be controlled by applying phase differences between signals, and the radiation pattern is narrower compared to other antennas. Electronic beam steering eliminates the need for physical movement, enhancing flexibility. Phase shifters enable the generation of multiple beams which is either analog or digital, depending on the application. Analog phase shifters achieve this by down-converting and time-shifting the signals, whereas digital phase shifters utilize phase shifts through intermediate frequency mixers and local oscillator signals. Phased array antennas generally have lower weight and cost compared to mechanically steered single-element antennas (119). Another cost efficient method to effectively implement digital beamforming on phased array inspired by the concept of transmit beamforming by introducing the delays to focus the beams in a desired direction (120) (121). However, during system deployment, phased array antennas face challenges such as the need for proper element spacing to avoid grating lobes. The arrangement of numerous antenna elements and phase shifters in a compact design is complex. Inaccurate phase differences can lead to beam squinting. Additionally, components in phased array antennas consume significant power, requiring high power sources, and interference handling between array elements and the external environment necessitates complex signal processing techniques. The high-speed multichannel radar signal data acquisition system is crucial for FOPEN radar, enabling the simultaneous capture, processing, and analysis of radar signals from multiple channels. This capability enhances the radar's ability to detect and differentiate targets hidden behind foliage by efficiently handling complex, real-time signal data across multiple frequencies (122).

6. INTRODUCTION TO BEAMFORMING

In antenna beamforming, the shape of the antenna beam is controlled using digital signal processing. This technique involves processing the signals received or transmitted by each antenna element to electronically form a desired beam pattern. This allows for precise control of the beam's direction, shape, and focus **(123).** Digital beamforming in antennas involves the following steps: each antenna in the array receives an incoming signal, which is then converted to digital signals using an ADC. These digitized signals are processed by a DSP, which adjusts phases and amplitudes based on the desired beam direction. By making proper adjustments in these phases and amplitudes, the signals can be combined constructively to form the beam in the desired direction. Digital beamforming is classed into four types: single-channel, multi-channel, adaptive, and hybrid. Single-channel digital beamforming uses digital processing on a single channel for beam creation and guiding, which is simpler but less flexible than other methods. Multi-channel digital beamforming handles several channels independently, allowing for more advanced beam shaping and improved performance in multipath conditions. Adaptive digital beamforming (124) automatically alters beam patterns in response to real-time environmental feedback, thus enhancing signal quality and interference management. Hybrid beamforming combines digital and analog techniques to create a mix of performance and complexity, making it ideal for systems that demand great efficiency and adaptability. For FOPEN applications, MIMO antennas (Multi-Channel Digital Beamforming) (125**)** is preferred due to its advantages over other antennas used in the conventional radars, such as higher resolution, improved angle estimation accuracy, increased number of target detections, larger array aperture, and waveform diversity. Unlike

Single-Channel Digital Beamforming, MIMO uses multiple RF chains for greater accuracy, wider beamwidth, and faster response (126).

For our design, we use the Butler Matrix for beamforming. The Butler Matrix is a passive network that generates multiple beams from the antenna array and electronically steers the beam to generate a strong beam in the desired direction while minimizing interference. It consists of phase shifters, hybrid couplers, and crossover elements arranged to provide phase shifts and amplitude distribution for the antenna elements (127). The Butler Matrix allows control over the radiation pattern by enabling the main beam to be steered in various directions. This capability is crucial for Foliage Penetration applications, as it helps detect targets under dense foliage. Due to its compactness, the Butler Matrix facilitates easy deployment in various environmental conditions. It enhances power and signal-to-noise ratio by providing specific directivity to the beam. To improve detection, spatial filtering is used to remove clutter between foliage and the actual target. The Butler Matrix can operate effectively at lower frequencies typical for FOPEN radars by making appropriate adjustments in phase and amplitude (128).

6.1 Beamforming Techniques for FOPEN Radar

Various beamforming techniques have been developed to improve the performance of radar systems, each with distinct advantages and limitations. The following sections discuss the most relevant beamforming methods for FOPEN radar applications.

6.1.1 Narrowband Beamforming

Narrowband beamforming involves instantaneous linear combining of the received array signals. While it is effective for conventional radar systems operating with narrowband signals, it may face limitations in FOPEN radar due to the wideband nature of the signals needed to penetrate dense foliage. Narrowband beamforming can be beneficial in applications where high-resolution directional accuracy is required but is generally less effective in wideband FOPEN systems.

6.1.2 Wideband Beamforming

Wideband beamforming, which applies spatial filtering to wideband signals, is more suitable for FOPEN radar systems due to the broader frequency spectrum used to penetrate foliage. This technique enables the system to handle high-frequency band transmissions, which are essential for achieving high data rates and enhanced penetration capabilities. The ability to maintain beam coherence across a wide frequency range is crucial for accurate target detection in dense vegetation environments.

6.1.3 Zero Forcing (ZF) Beamforming

Zero-forcing (ZF) beamforming is a spatial signal processing technique that minimizes interference by nullifying unwanted signals. This method can be effective in FOPEN radar when multiple targets are present in the cluttered environment, as it allows the radar to isolate desired signals from those caused by foliage scatter. However, ZF requires precise knowledge of the channel state information (CSI), which may be challenging to obtain in dynamic FOPEN scenarios.

6.1.4 Analog Beamforming

Analog beamforming involves varying the amplitude and phase of signals in the analog domain, allowing the beam to be directed toward specific targets with minimal hardware complexity. This method is cost-effective and can be implemented with low power consumption, making it attractive for portable FOPEN radar systems. However, analog beamforming lacks the flexibility and precision of digital techniques, which may limit its performance in complex environments.

6.1.5 Digital Beamforming (DBF)

Digital beamforming offers greater flexibility and precision by allowing signal processing in the digital domain before conversion to analog. This technique enables advanced features such as adaptive pattern nulling, closely spaced multiple beams, and super-resolution, making it highly suitable for FOPEN radar. DBF also allows for real-time adjustments based on the radar's environment, enhancing the radar's ability to penetrate foliage and accurately detect hidden objects.

6.1.6 Hybrid Beamforming

Hybrid beamforming combines the advantages of both analog and digital beamforming, offering a balance between cost, power consumption, and performance. In FOPEN radar, hybrid beamforming can be used to optimize the trade-off between system complexity and the ability to penetrate dense foliage. This technique is particularly relevant for 5G-based FOPEN radar systems, where high data rates and low-latency processing are essential for real-time target detection.

6.1.7 Adaptive Beamforming

Adaptive beamforming is one of the most critical techniques for FOPEN radar, as it dynamically adjusts the beam direction based on environmental conditions and target movement. This method uses feedback from the radar system to continually refine the beam's focus, minimizing interference from foliage and enhancing target detection. Adaptive beamforming is often used in conjunction with MIMO radar systems, where multiple transmit and receive antennas work together to optimize beam direction and improve system performance.Adaptive digital beamforming (67) automatically alters beam patterns in response to real-time environmental feedback, thus enhancing signal quality and interference management. Hybrid beamforming combines digital and analog techniques to create a mix of performance and complexity, making it ideal for systems that demand great efficiency and adaptability.

7. MIMO BEAMFORMING IN FOPEN RADAR

Due to its ability to improve signal diversity and spatial resolutionMIMO systems employ multiple antennas for both transmission and reception, enabling the radar to direct energy towards specific regions and enhance its capability to penetrate foliage. By employing adaptive beamforming techniques, MIMO-FOPEN radar systems can dynamically adjust the beam pattern to account for changing environmental conditions, significantly improving detection performance.MIMO antennas (Multi-Channel Digital Beamforming) (68) is preferred due to its advantages over other antennas used in the conventional radars, such as higher resolution, improved angle estimation accuracy, increased number of target detections, larger array aperture, and waveform diversity. Unlike Single-Channel Digital Beamforming, MIMO uses multiple RF chains for greater accuracy, wider beamwidth, and faster response (69).In lower frequency bands with array antenna MIMO radar is used such that array antenna ensures low side-lobes. In lower frequency bands, MIMO radar systems utilize array antennas to achieve low side-lobes, thereby improving signal clarity and reducing unwanted interference.

Table VI: Comparison of Beamforming Techniques for FOPEN Radar

Technique	Penetration through Foliage	Target Detection Accuracy	Power Consumption	Adaptability to Environment	Cost
Narrowband	Low	Medium	Low	Low	Low
Wideband	High	High	Medium	Medium	Medium
Zero Forcing	Medium	High	Medium	Medium	Medium
Analog	Low	Medium	Low	Low	Low
Digital	High	Very High	High	High	High
Hybrid	High	High	Medium	High	Medium
Adaptive	Very High	Very High	Medium	Very High	High
MIMO	Very High	Very High	High	Very High	High

8. CONCLUSION

This paper demonstrates the pivotal role of antenna technologies in the advancement and operation of Foliage Penetration Radar (FOPEN) systems. The historical evolution of these technologies underscores their critical importance in detecting targets obscured by dense vegetation. Antennas in FOPEN systems are classified based on operational requirements and system configurations, reflecting the diverse design considerations that shape system performance. Key advancements, including phased array and adaptive array technologies, have significantly enhanced radar capabilities by improving resolution, detection range, and adaptability to challenging environments. Phased array systems, in particular, allow for agile beam steering and improved target localization, while adaptive arrays further optimize performance through dynamic adjustment to environmental conditions. The integration of advanced beamforming techniques has resulted in substantial improvements in signal-to-noise ratio (SNR), contributing to more effective signal processing. However, challenges remain in achieving an optimal balance between wideband operation, directivity, and polarization diversity, which are critical for optimizing foliage penetration. These factors continue to pose significant design challenges, particularly when attempting to maintain system efficiency across varying terrain and environmental conditions. Future research should focus on overcoming these challenges by advancing antenna designs that support wideband, high-directivity, and polarization-diverse operation to meet the demands of next-generation FOPEN radar systems. Continued innovation in these areas will further enhance target detection capabilities, system adaptability, and overall operational efficiency in complex environments.

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