

Review

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Posted Date: 24 June 2024

doi: 10.20944/preprints202405.0609.v2

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Review

Innovations and Applications of Millimeter Wave Antennas: A Literature Review

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Abstract: Millimeter wave antennas have significance for high-speed, high-capacity wireless communication, delivering substantial advantages and an array of applications. This literature review analyzes the historical development, assessment of performance, difficulties with design, and contemporary applications in telecommunications, radar systems, and imaging. It covers the development of technology, especially within the context of 5G and beyond, and focuses at several antenna designs that deal with technical issues including reduction and impedance matching. The review also studies the effect of design on efficiency and bandwidth, identifying research gaps and potential futures, notably in terms of 5G technology. The commitment to develop millimeter wave antenna technology for next-generation wireless networks is evident, underlining the need of continued research and development.

Keywords: millimeter wave; antenna; communications; bandwidth; gain

1. Introduction

There are different millimeter wave antennas developed for various applications. A broadband with circularly polarized antenna utilized for 5G communication is proposed by Li et al. [1]. Also, Kare and Jyothi [2] developed a compact MIMO antenna that utilized millimeter wave technology. For system-on chip purposes, Agarwal [3] creates dual band millimeter antenna for its application. A proposed antenna by Fu et al. [4] is a good option for 5G mobile communication which is compact and has low cross polarization. However, there is also a triple-band millimeter antenna created by Parveez et al. [5] to be used for wearable devices because of its flexibility. These articles exhibit the capability of millimeter antennas with its various advantages to deliver the signal in high-speed, high-capacity wireless communication. This literature review analyzes the advances and applications of millimeter wave (mmWave) antennas. It tackles a wide variety of topics including the historical development of mmWave antenna technology, measurement of performance, design issues, and current applications in telecommunications, radar systems, and imaging. This article also addresses the challenges experienced during the construction and installation of mmWave antennas and identifies areas of opportunity for further research. The objectives of this literature review on millimeter wave antennas are to provide a comprehensive overview of its development, evaluate important performance metrics such as gain and bandwidth, investigate different applications in communication and radar systems, identify the challenges, and guide future research to enhance antenna capabilities and close existing gaps.

2. Materials and Methods

In this part, the systematic approach used to gather the related literature on millimeter wave antennas is described

2.1. Search Strategy

The search approach includes accessing multiple databases, including IEEE Xplore, ScienceDirect, and Google Scholar to identify which article will be use for the literature review.

2.2. Selection Criteria

The studies included millimeter wave antenna design, assessment of performance, and applications which published from January 1, 2019. Non-peer-reviewed sources, duplicate research, and those unrelated to antennas have been among the exclusion criteria. Language limitations were not implemented, ensuring an extensive review.

2.3. Data Extraction

Data extraction involves extracting important data from each study. Details such as antenna types, frequency bands, and design characteristics were collected. The extracted data was inserted into a structured database for further research.

2.4. Quality Assessment

A set of criteria was created to assess the quality of the studies. These criteria were scientific validity, experimental methodology, and relevance to the review objectives. The quality assessment approach was carefully developed to ensure objectivity and consistency. Potential biases were addressed by thorough self-evaluation and critical reflection. Multiple points of view were carefully explored and resolved by careful examination and refinement.

3. Results and Discussions

3.1. Evolution of Millimeter Wave Antenna Technology

3.1.1. Historical Perspective

Wireless systems have developed over the past five decades, from offering voice applications to improved mobile broadband. To keep up with the ever-increasing data rate demands of wireless systems, bands of frequencies covering an extensive range from 800 MHz to 100 GHz have been assigned for use [6]. The demand for high-speed, seamless wireless solutions has propelled the evolution of millimeter-wave (mm-wave) antenna technology, particularly in the context of 5G and beyond [7,8]. Additionally, for more than a half-century, phased-array antenna technology has made an extensive effect that spans from radar to radio astronomy, and it is set to start a major change in the operation of mobile communications [9]. These innovation influenced the development of cellular phones which used frequency modulated array and phased-array antennas [10,11].

3.1.2. Recent Developments

Innovations in millimeter wave antenna technology have aim to improve the capability and performance of the antennas. Polo-Lopez et al. [12] created prototypes intended for the next generation of millimeter-wave-based communication systems. The prototypes included were planned to be created utilizing several innovative methods, including subtractive and additive approaches. The prototypes are composed of a monopulse antenna with a mode converter, comparator network, and a spline profile horn; a tunable phase shifter embedded in an array that enables for reconfigurability of the main lobe direction; and a conformal array antenna. Khan et al. [13] presented a new patch dual-polarized antenna with capacitive feeding. This property is achieved by utilizing two orthogonal feeds for linear and circular polarizations. This antenna works effectively from 57 to 63 GHz, which encompasses the 6 GHz ISM band. The reflection coefficients are notably below -10dB over the whole 6 GHz range. The mutual coupling rates are less than -25dB. The total efficiency is approximately 86%. Rohan et al. [14] developed a planar microstrip patch antenna for 5G wireless and millimeter wave communication. Several slots have been added for better

performance. This antenna is beneficial for 5G wireless communication since it can operate at a millimeter wave frequency of 54GHz while complying to IEEE 802.11ad standards. The dual-array antenna system has been made by Tahseen et al. [15] for different wireless applications of 5G mm-Wave. It employs a series feed line compact approach that allows two arrays on the same substrate edges. The profile antenna system has two 1x16 arrays on similar substrate edges. Each array offers 17.3 dB and 16.4 dB simulated and measured gains, respectively, in addition to impedance bandwidth from 31.30 GHz to 39 GHz at a central frequency of 38 GHz. The capacity for using both arrays simultaneously for two separate applications inside the operating band for the same or different center frequencies implies this proposed dual-array antenna system a good option for 5G mm-Wave wireless IoT and broadcast applications. An innovative slot array antenna that utilizes substrate-integrated double-line (SIDL) technology is presented by Guo and Hao [16]. SIDL technology optimizes the feed network of array while suppressing the high-order mode. As a result, the antenna can be built with minimal dimension, a significant radiation efficiency, and an extensive bandwidth. To stimulate the antenna, the microstrip-to-SIDL transition is assembled with coupling gaps on the bottom plate of the SIDL. The determined -10 dB impedance bandwidth ranges from 23.35 to 27.55 GHz (16.5%). The simulations yielded a 21.6 dBi gain at the stated frequency of 25.8 GHz. The reported 1 dB gain bandwidth and the simulated radiation efficiency are 12.5% and 75%, correspondingly. The antenna can be applied to develop compact and efficient millimeter-wave systems.

3.2. Performance Metrics and Design Considerations

3.2.1. Antenna Gain and Directivity

There are many millimeter wave antennas equipped with different design features. A circularly polarized cylindrical cavity-backed substrate embedded waveguide resonator for millimeter wave applications has been proposed by Tewari et al. [17]. Two symmetrical rectangular slots are diagonally set up on the top metal plane of the cavity, and the feed site is designed for better impedance matching. The suggested antenna with feeding structure has dimensions of $3.55\lambda \times 3.56\lambda \times 0.19\lambda$, where λ corresponds to the guided wavelength. The antenna obtains a maximum gain of 5.85dBi, peak directivity of 6.23dBi, radiation efficiency of 94.1%, and an axial ratio of 120MHz bandwidth lower than 3dB. The proposed antenna of Orakwue and Onu [18] is meant to operate at a mm-wave frequency of 17 GHz. Circular antennas offer a low return loss while providing more gain and directivity. The array is mainly utilized to increase the gain of antenna. The antenna was developed adopting the inset feed approach. Design formulas determine both the size and the feeding strategy. These studies demonstrate the possibility for high gain and directivity in millimeter wave antennas employing a range of design techniques and performance measurements.

3.2.2. Bandwidth and Efficiency

Many studies have tackled the influence of the design considerations and performance measures in bandwidth and efficiency. To tackle these issues and fulfill 5G communication requirements, an antenna with narrow steerable beam, multiband properties, wide bandwidth, high gain, high isolation, high isolation, and low side-lobe levels is required [19]. According to Juneja and Sharma [20], Millimeter wave (mmW) frequency communication at 28 GHz and 38 GHz, which are being studied for application in next-generation cellular communication networks (i.e., 5G), suffer from substantial interference in the surrounding environment. Therefore, efficient and intelligent antenna design techniques are required for proper transmission and reception of signals at mmW frequencies.

The article of Mohamed [21] implied that the feeding procedure on antenna features dielectric constant, and substrate thickness. The inset feeder exhibited a bandwidth of up to 1 GHz, and some feed mechanisms were evaluated and tested. The prepared rectangular patch antenna has a return loss value of lower than -24.67dB with a bandwidth of 2.71GHz. Moreover, there is an effective directivity value of 9.34 dBi, an antenna gain of 6.51 dBi, and a high antenna efficiency of 75.10%. The most effectively optimized single element patch, produced at 28 GHz to meet the needs of 5G antennas, utilized the Advanced Design System (ADS) simulators to create the single element. Also,

Shakir et al. [22] improve the efficiency of their antenna up to 20% by studying transmission losses and applying antenna design with varying substrate thicknesses. This approach allows them to determine the variance in radiation properties, such as input impedance, gain, and radiation efficiency, particularly in the 5G mm-wave spectrum. Through mathematical modeling, they analyze how changes in substrate thickness affect these properties, ultimately leading to the enhancement of antenna efficiency by up to 20%. Both studies highlight the importance of efficiency and antenna gain.

Issa et al. [23] presented a double-layer antenna concept that is different from those that were used in millimeter-wave communication applications. The objective is to increase gain while also increasing efficiency and bandwidth. The demonstrated reflection coefficient of the design attains a bandwidth of 20.66% from 53.9 GHz to 66.3 GHz, which includes the whole frequency range of interest. In addition, this proposed structure has a maximum realized gain of 11.8 dBi and an estimated radiation efficiency of 91.2%. The chosen antenna is simulated, built, and tested in an anechoic chamber environment. The measurement data illustrate an equitable agreement with the modeling findings in terms of gain, bandwidth, and side-lobe level in the operating spectrum. These studies demonstrate the potential for efficient and large performance in millimeter-wave antennas, which have usages in industrial, 5G, and other wireless communication systems.

3.3. Applications of Millimeter Wave Antennas

3.3.1. Telecommunications

Recent researches have focused on the design of millimeter wave antennas for several telecommunications applications. Fifth generation mobile communication technology (5G) is one of the uses of millimeter wave which is currently increasing [24]. A microstrip antenna intended for broadband millimeter wave mobile communication is proposed by Han et al. [25]. The microstrip antenna runs by a coplanar waveguide (CPW) design, with a matching port coupled to a 50-Ω resistor. The performing bandwidth of antenna includes both the 28 GHz and 39 GHz bands, making it ideal for 5G millimeter wave applications. Hussain [26] demonstrates an umbrella-shaped patch antenna to be used for millimeter-wave applications. The proposed antenna resonates across multiple frequency bands, including 28 GHz, 38 GHz, and 55 GHz (V-band), that have been internationally assigned for 5G communications systems. The work of Tariq et al. [27] describes a 4-element multiple-input multiple-output (MIMO) antenna with a single multiple-layer metasurface array for 5G millimeter-wave (mm-Wave) communication systems. Each MIMO antenna element comprises a 1×2 array that has a corporate feed network. Additionally, A metasurface array consisting of 9×6 Circular Split Ring (CSR) cells is utilized to enhance the gain and isolation of the MIMO antenna components. Zada et al. [28] illustrate a compact-size dual-function antenna for 5G mobile applications at 3.5 GHz and the mm-wave band (28 GHz) which is compatible to the upcoming 5G devices.

As millimeter wave antennas enable high-bandwidth communications in emerging 5G and beyond networks, the implementation of advanced encryption methods such as this enhanced hybrid algorithm combining chaos-based systems, AES, RSA, and ElGamal could be crucial in securing the vast amounts of sensitive data transmitted over these high-frequency channels, addressing potential vulnerabilities unique to millimeter wave propagation characteristics [29]. These investigations emphasize the use of millimeter wave antennas in telecommunications, particularly in the context of 5G and beyond.

3.3.2. Radar Systems

Several studies about interesting millimeter wave antennas have applications specifically for radar is created. Hu et al. [30] constructed a microstrip antenna unit with a higher impedance bandwidth that is ideal for phased array radar systems. De Cos Gómez et al. [31] demonstrated a low-cost, sustainable PP-based array antenna for wearable radar systems, which improved beam width, side-lobe level, and gain. Wu et al. [32] proposed a 3D all-metal antenna array for motor vehicle radar with an extensive operational bandwidth and low sidelobe level. Qian et al. [33] devised a through-hole antenna array for combined optical and millimeter sensing, incorporating optical

imaging cameras to deliver good sensing results. The proposed antenna array by Tang et al. [34]. has significant promise for application in flexible wireless mmWave communication systems and 3D-printed flexible radar systems. Rahmat Ali et al. [35] describe a possible tetra band Mm-wave antenna ($9 \times 8 \times 0.127$ mm³) with an extensive ground plane for Ka, V, and W-band applications, making it optimal for radar applications and high-speed military. These studies reveal the numerous and possible uses of millimeter wave antennas in radar systems.

3.3.3. Imaging and Sensing

Recent research has examined a wide range of millimeter wave antenna applications in imaging and sensing. Panigrahi et al. [36] devised a waveguide transmitarray antenna for near-field millimeter-wave sensing, that has potential uses in medicine, food safety, and industry. Meredov et al. [37] invented a screen-printed, flexible, parasitic beam-switching millimeter-wave antenna array for wearable applications, such as a high gain of 11.2 dBi and three separate beams. Al-Alem et al. [38] revealed a high gain millimeter-wave planar antenna array for sensing and radar applications, which features a realized gain of 20 dBi and a matching bandwidth of 4.1%. While our literature review focuses on millimeter wave antennas, the integration of such advanced wireless communication technologies could potentially enhance the range and reliability of microcontroller-based monitoring systems like the Android-accessible reservoir water level monitor, enabling more efficient data transmission in remote or challenging environments [39]. These studies show the possibilities of millimeter wave antennas in a number of imaging and sensing applications.

3.4. Challenges and Future Direction

3.4.1. Technical Challenges

The application of millimeter-wave frequencies in wireless communication systems has different technological difficulties, including decreased amplifier efficiency and larger route loss [40]. To get around these issues, high-gain antenna designs have been created that can operate at lower power levels while still producing high effective isotropic radiated power [40]. Also, improvements to antenna array technologies, such as agile beamforming with wide-scan capabilities, have been studied to improve point-to-point and point-to-multipoint wireless communications at millimeter-wave frequencies [41]. Miniaturization and impedance matching are also significant hurdles in millimeter-wave antenna design, with new forms offered to overcome these concerns, such as a 30 GHz microstrip patch antenna [42].

3.4.2. Research Gaps

Millimeter-wave (mm-wave) transmitters are frequently manufactured making use of modern technology, requiring a complex production facility. However, the literature continues to present certain gaps [43]. For instance, while Kaushal and Guan [44] developed a broadband millimeter wave array antenna, its specific issues and uses for 5G technology are still not fully explored. Singh et al. [45] emphasizes the need for more study in this field, especially within the context of microstrip patch antennas and their potential to enhance mobile phone performance. Future research should address these gaps by examining the design considerations and uses of millimeter wave antennas, especially within the context of 5G technology.

4. Conclusions

The article gives an in-depth evaluation of millimeter wave antenna advancements and applications concentrating on their substantial evolution and current attempts to further develop their capabilities for future technologies such as 5G. It investigates the evolution of antenna technology and advances aimed at increasing metrics for performance such as gain and bandwidth. The work further looks at several antenna designs, addressing the technical issues of downsizing and good impedance matching, which are vital to effective operation. Furthermore, it analyzes the impact

of various designs on the overall efficiency and bandwidth of antennas. Looking in the future, this paper outlines existing research gaps and presents future research possibilities, with an emphasis on studying design concerns and potential applications in the rapidly developing field of 5G technology. This indicates the continued commitment to developing millimeter wave antenna technology to meet the needs of next-generation wireless communication systems.

Conflicts of Interest: The authors declare that they have no known competing of interest.

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