Conference Proceedings: "Sustainability Through Digital Transformation: Insights from Management, Humanities, and Sciences" SDT– Insights 2026, Organized by- The Ashoka Institute of Technology and Management, Varanasi (30–31 January 2026) In IJRT ISSN: 2321-7529

Challenges, Design, and Innovations in mmWave Antennas for 6G and beyond Wireless Systems: A Survey

---

[1]Pradeep Kumar Verma, [2]Anuja Singh,[3]Lalit Kumar,[4]Pankaj Vishwakarma
[1,2,3,4]Department of Electronics & Communication Engineering
[1,2,3,4]Ashoka Institute of Technology & Management,Varanasi, India
[1]verma.pradeepecaitm@gmail.com, [2]anujasingh.ec@gmail.com, [3]lalitece1027@gmail.com, [4]pv1409@gmail.com
https://doi.org/10.64882/ijrt.v14.iS1.1123

Abstract

Millimeter-wave (mmWave) bands i.e.30 GHz to 300 GHz is the key for 6G wireless systems, that offers ultra-wide bandwidths, low latency and very high data rates. However, the design of mmWave antennas have many challenges like propagation losses, beamforming, cost, efficiency, size and many more. This paper is a survey that focusses on mmWave antenna design, design approaches to overcome challenges in antenna design and some simulation results for mmWave antenna design. There are various approaches for antenna design like using metamaterials/ metasurfaces, defected ground structures (DGS) and antenna-in-package (AiP) technology to realize a compact antenna array with high gain, wide bandwidth and reconfigurable beam-steering functionalities.

Keywords—6G, mmWave, antenna array, metamaterials, defected ground structure, antenna-in-package (AiP), MIMO, ultra-wide band, ISAC, LCP.

INTRODUCTION

The emergence of 6G wireless systems promises in paradigm shift in existing wireless systems moving towards very-high data rates, seamless connectivity, immersive user experience and integrated sensing capabilities. To realize these goals the key will be utilization of millimeter-wave (mmWave) frequency bands (30-300 GHz) Terrahertz (THz) frequency bands. These are unused spectrum which can be used for multi-Gbps throughput and ultra-low latency, but it also brings new challenges in antenna design, propagation, integration and implementation.

This paper tries to address the design, challenges and innovations in mmWave antennas specifically for 6G wireless systems. The ffundamental design criteria for antennas and arrays operating at mmWave frequencies—including wide bandwidth, high gain, beamforming, element isolation, polarization diversity, and compact form factors will be discussed. The main challenges that must be addressed are path loss, blockage and atmospheric absorption: mutual coupling and efficiency degradation, power consumption, material losses, complexity etc.

The recent technological advancements offer some solutions, which include use of metasurfaces and reconfigurable intelligent surfaces (RIS), hybrid MIMO architectures, antenna-in-package and other integration technologies and AI/ML assisted design and beam control. These approaches help to solve many of the above-mentioned challenges, resulting in better performance, high efficiency, and more reliable connectivity specifically in non-ideal, mobile, or obstructed scenario.

I. BACKGROUND

A. Propagation and channel characteristics

The mmWave band suffers from high path loss as evident from Friis transmission equation which says that the received power is inversely proportional to the square of the frequency and as the frequency increases the free-space path loss also increases. [1]

The mmWave frequencies have very small wavelengths (a few millimeters) that is why objects and edges don't bend the wave much results in minimal diffraction and barriers like walls, foliage, human bodies act almost like solid blocks [2]. Even the penetration through materials is much worse as standard walls can cause tens of dB attenuation. [3]

Atmospheric absorption by gases in the air specifically water vapor and oxygen of mmWave frequencies are significant and shows its peak at around 60 GHz[4]. Rain droplets scatter and absorb mmWave signal , adding loss, especially in heavy rain.[4] Foliage, humidity, fog also add to scattering/absorption losses.[2]

Due to the intense research carried out through the years in mmWave frequency bands the challenges discussed in previous paragraphs have somewhat being answered by researchers and they have come up with solutions like Beamforming and Beam management. Beamforming is a process of shaping and directing radio signals using an array of antennas, on the other hand beam management is dynamic control of beam directions to optimize communication quality, particularly in mobile and heterogeneous network environments [5]. Advantage of beamforming is its ability to increase signal strength, extend coverage and reduced interference in high frequency bands like mmWave.

This article covers three types of beamforming namely Analog beamforming, Digital beamforming and Hybrid beamforming. In analog beamforming phase shifters are used to adjust the phase of each antenna element, aligning the signal in a specific direction without the need of any complex signal processing at each antenna. This process is simple but restricted in terms of flexibility and precision. On the other hand, in digital beamforming the signal is processed digitally before being transmitted to the antenna, allowing more flexible and adaptive beam steering. This allows adaptive beamforming, here the system dynamically adjusts the direction based on changing conditions, such as user mobility or interference. Hybrid beamforming combines both analog and digital beamforming to take the advantage of the low power consumption and simplicity of analog one while providing the flexibility and accuracy of digital processing. Beamforming offers solutions to many issues but have its own limitations which include hardware limitations, feedback delays and complexity of handling dynamic interference in real-time. As the technology advances much more AI/ML based beamforming algorithms and hardware design are expected to find solution of these issues and enable more efficient beamforming techniques in the future [5][6].

Beam management is the process of controlling, maintaining, and optimizing the direction of the beams during a communication session. This process is crucial for mobile users who have changing environment conditions like motion, blockage, or interference. Efficient beam management ensures that the communication link remains stable, high-quality and free from disruptions. The key components of beam management are beam initialization, beam tracking, beam switching and handover and beam reconfiguration. Beam initialization identifies the most appropriate beam direction at the start of a communication. This process involves scanning the environment for detection of optimal beam that offers highest signal strength or lowest interference. Beam tracking is continuous monitoring and adjusting the beam in real-time, ensuring that the signal remains strong and stable. Beam switching and handover happens in high-speed mobile environments like vehicular communications or drones where user moves out of the coverage area of the current beam, at this time system needs to seamlessly handover the communication link to a new beam. This process is essential for maintaining uninterrupted service. Beam reconfiguration is the ability to adapt the beam’s direction and shape based on changing conditions for optimizing signal quality. There are some challenges regarding beam management that is beam reconfiguration for high-speed mobile users [6].

II. CHALLENGES IN MMWAVE ANTENNA DESIGN

A. Propagation losses and blocking

Both mm Wave and THz frequencies suffer from much larger free-space path loss than lower bands. In the THz region especially, absorption by atmospheric molecules (e.g.water vapor, oxygen) can severely attenuate signals. This reduces transmission ranges and imposes requirements of high-gain, highly directional antennas. Physical obstacles (buildings, foliage, human bodies) block or scatter high-frequency waves more strongly; diffraction (bending around edges) is less effective. This makes line-of-sight (LOS) or quasi-LOS paths more important. Dynamic environments (mobile users, moving obstacles) make the problem worse. At very high frequencies, the multipath richness tends to reduce; there may be fewer dominant paths. This reduces spatial multiplexing gains unless antenna arrays are cleverly designed (e.g.widely spaced subarrays) to reduce correlation. Also, wide bandwidths lead to *channel variation in frequency* (frequency-selective fading) and phase errors (channel “squint”) in beamforming [7].

B. Antenna Array Design and Beamforming

The wavelengths of mm Wave and THz are small, so, more antenna elements can be packed into a given aperture. But integrating thousands of elements brings its own set of challenges like mutual coupling, element isolation, precise element placement and feed network complexity. To compensate for the losses during communication narrow beams are required and these beams must be aligned, tracked and adjusted as per the movement of the user. Initial access (beam training) and continual beam tracking are more complex with narrow beams, high mobility, and dynamic environments this increases overhead. In wideband systems, steering with traditional phase shifters may lead to beam directions shifting with frequency (beam squint). For large scan angles and wide fractional bandwidths this becomes pronounced, degrading performance. True time delay (TTD) implementations or other compensation schemes are needed [7].

C. Materials, Fabrication, and Physical Realization

Dielectric materials tend to have higher loss tangent at mmWave/THz frequencies; conductor losses increase due to skin effect and surface roughness. Efficient antenna designs need low-loss dielectrics, good conductor surfaces, and minimal parasitic effects [8]. Since, physical dimensions are small (fraction of millimeter down towards micron or even sub-micron), fabrication tolerances become critical. Surface roughness, misalignment, inconsistent metallization, etc., can cause significant losses or degrade radiation/pattern properties. Many of the current techniques (e.g., high-resolution lithography, 3D micromachining, additive printing) are still expensive, or difficult to scale to large production volumes. Also, the associated measurement and metrology tools are costly and less mature in THz bands [9][10][11][12].

D. Integration & Packaged Systems

Antenna-in-package (AiP), on-chip/on-array integration: As arrays grow, integrating the antenna elements with RF electronics (amplifiers, phase shifters, LO, mixers) becomes necessary. Interconnect losses, coupling between elements, impedance matching, thermal issues, and aligning electrical behavior with mechanical layout are complex [8][13][14].

Power efficiency, heat dissipation & power amplifiers: PA design at mm Wave/THz is challenging: efficiency, linearity, output power are worse than at lower bands. When many PAs or active devices are close, heat dissipation becomes a serious concern. Also, battery-powered or portable devices must manage power and thermal constraints [8].

E. Measurement, Standardization, and Testing

- **Lack of mature measurement infrastructure**: Calibrated measurement for S-parameters, radiation patterns, gain, beamforming performance at THz is more difficult because of the need for specialized probes, waveguides, optical components, and limited availability of standard testbeds [15].
- **Standards, reference models, benchmarking**: Without agreed-upon standards and practices, comparing designs becomes harder; channel models in realistic environments (urban, indoor, mobility) are still under development [8].

F. System-Level & Operational Constraints

- **Mobility, alignment, tracking overhead**: As noted, moving users or devices (e.g. in vehicles, drones, handhelds) introduce misalignments, beam switching; fast beam training/tracking is required, which adds overhead and latency [16].
- **Environmental sensitivity and robustness**: Rain, humidity, temperature variations, vibrations, mechanical tolerances — all can impact antenna performance, especially gain, pointing accuracy, polarization. THz wavelengths are so small that even small mechanical changes can matter [17][18].

III. FUTURE ASPECTS IN ANTENNA DESIGN

- **ISAC**: Integrated Sensing and Communication is **reconfigurable, large-scale, and high-frequency systems** that can sense their environment while transmitting data. It can overcome high-frequency propagation losses (mm Wave and THz) and utilizes the spatial information provided by large antenna array [19][20].
- **Antenna-on-Chip (AoC) & Antenna-in-Package (AiP):** To save the space and to reduce the loss of signal, nowadays the external antennas are becoming obsolete and instead of this the antennas are built directly within the RF chip called antenna-on-chip or antenna-in-package. This could eliminate the signal loss that occurs when it propagates through the medium to the feed of the external antenna[14].

- **Filtering Antennas (Filtennas):** These are antennas which have the combined functionality of filtering and radiating. Thus instead of having separate modules for filtering the signals and radiating them in the environment, a single module would be able to do both the tasks and may reduce the size and cost of the antenna. It also drastically improves noise performance of the antenna and reduces the overall footprint[21].
- **Green Antennas:** These antennas are made using low-carbon, recyclable materials. This also uses solar or RF energy harvesting features that can power low-energy IoT devices without needing batteries[22].
- **Flexible and Wearable Designs:** Groundbreaking breakthroughs in nanomaterials and advanced printing techniques have enabled antennas that can be printed onto textiles or skin patches. These antennas are designed to withstand bending and stretching while remaining safe for the human body[23].
- **Movable and Fluid Antenna Systems**:
  Dynamic Spatial Optimization: Emerging **Movable Antennas (MA)** and **Fluid Antennas (FAS)** can physically or virtually adjust their positions within a small area to exploit the best channel conditions [24].
- **MIMO Enhancement:** By optimizing antenna placement in real-time, these systems can achieve the performance of traditional massive MIMO with fewer active radio frequency (RF) chains, reducing cost and power consumption [16].
- **Smart and Reconfigurable Systems:** The next generation antennas would be "smart," and they can automatically adapt to their surrounding environment very easily.
- **Dynamic Reconfigurability:** Through integrated mechanisms like PIN diodes or tunable materials, a single antenna can change its operating frequency, polarization, or radiation pattern in real-time.
- **Interference Mitigation:** Smart antenna arrays use advanced algorithms to steer signals away from interference sources, enhancing network flexibility in noisy urban environments [25].
- **AI and Machine Learning Integration**

As Manual optimization is an impossible task as antenna complexity grows. Machine Learning (ML) is now a core part of the antenna design cycle.

- **Automated Optimization:** AI-driven frameworks, such as those using CatBoost algorithms, can predict performance metrics like return loss with high accuracy, drastically reducing the time spent on iterative simulations.
- **Real-time Adaptation:** In the field, AI helps manage massive MIMO arrays (often with hundreds of elements) by predicting channel conditions and optimizing beam patterns on the fly.

IV. CONCLUSION

mm Wave antennas are essential for providing the massive bandwidth required for Terabit-per-second speeds and high-resolution ISAC (Integrated Sensing and Communication) capabilities, such as centimeter-level localization. However, these systems face severe propagation loss**,** high sensitivity to physical blockages**,** and significant power consumption in dense hardware arrays. To solve this, design approaches are shifting toward Massive MIMO with beam-focusing **to** concentrate signal energy**,** Reconfigurable Intelligent Surfaces (RIS) to bypass obstacles via smart reflections, and Lens Antennas or Movable Antenna systems that maximize spatial efficiency while reducing the complexity of the radio frequency front-end.

mm Wave ISAC systems can now achieve multi-gigabit data rates and centimeter-level localization accuracy in controlled line-of-sight environments using massive MIMO and advanced beamforming. However, achieving consistent performance in the real world remains difficult due to severe blockage sensitivity, where even a human body can cause a 20–30 dB signal drop, leading to frequent link failures. Furthermore, the high cost of RF components and the thermal management required for dense antenna arrays make large-scale commercial deployment expensive, while the energy-efficient integration of high-resolution sensing into mobile devices without draining battery life remains a significant engineering hurdle.

Realizing the full potential of 6G ISAC and beyond requires a deep coordination between antenna design, material sciences, and signal processing, as no single area can solve the mm Wave constraints alone. While material sciences give low-loss substrates like Liquid Crystal Polymer (LCP) to minimize the signal attenuation, antenna design must focus on highly integrated arrays that fit within compact, thermal-constrained devices. Simultaneously, advanced signal processing algorithms are necessary to dynamically manage the dual functions of sensing and communication, using AI-driven beamforming to compensate for hardware imperfections and environmental blockages.

References

1. A. Jabbar et al., "60 GHz Programmable Dynamic Metasurface Antenna (DMA) for Next-Generation Communication, Sensing, and Imaging Applications: From Concept to Prototype," in IEEE Open Journal of Antennas and Propagation, vol. 5, no. 3, pp. 705-726, June 2024.
2. A. L. Sharon Giftsy, U. K. Kommuri and R. P. Dwivedi, "Flexible and Wearable Antenna for Biomedical Application: Progress and Opportunity," in IEEE Access, vol. 12, pp. 90016-90040, 2024.
3. A. Shafie, N. Yang, C. Han, J. M. Jornet, M. Juntti and T. Kürner, "Terahertz Communications for 6G and Beyond Wireless Networks: Challenges, Key Advancements, and Opportunities," in IEEE Network, vol. 37, no. 3, pp. 162-169, May/June 2023, doi: 10.1109/MNET.118.2200057.
4. A. Zahedi, R. Liyanapathirana and K. Thiyagarajan, "Biodegradable and Renewable Antennas for Green IoT Sensors: A Review," in IEEE Access, vol. 12, pp. 189749-189775, 2024.
5. Afahaene Edet Uya, Sanjee Lamsal, Srikanth Itapu, Frank X. Li, Pedro Cortes, Gianfranco Trovato, Lili Dong, “Design and Fabrication of Terahertz (THz) Antenna Using Aerosol Jet Printing”, July 2023 IEEE 23rd International Conference on Nanotechnology (NANO).

6. Asif, S., Pal, R., Dubey, V., Kumari, P., & Shrivastava, S. (2024). Internet of Things (IoT) Integration with 5G and 6G Wireless Technologies. In Advanced IoT Technologies and Applications in the Industry 4.0 Digital Economy (pp. 309-327). CRC Press.
7. Atta Ullah, Daniyal Munir, Daniel Lindenschmitt, Hans D. Schotten, “Wideband Coplanar Waveguide MIMO Antenna for 6G Millimeter-Wave Applications with Defected Ground Structure”, IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting (AP-S/CNC-USNC-URSI) July 2025..
8. Azizul Islam; Daniel Adu-Gyamfi; Srikanth Itapu; Frank X. Li; Pedro Cortes; Vamsi Borra, “Design and Fabrication of a Terahertz Antenna Using Two-Photon Polymerization”, October 2024 IEEE Nanotechnology Materials and Devices Conference (NMDC).
9. C. X. Mao, Y. Zhang, X. Y. Zhang, P. Xiao, Y. Wang and S. Gao, "Filtering Antennas: Design Methods and Recent Developments," in IEEE Microwave Magazine, vol. 22, no. 11, pp. 52-63, Nov. 2021.
10. Faisal Mehmood, Asif Mehmood, “Recent Advancements in Millimeter-Wave Antennas and Arrays: From Compact Wearable Designs to Beam-Steering Technologies”, Electronics 2025, 14, 2705, https://doi.org/10.3390/electronics 14132705.
11. H. Ma, "Integrated Sensing and Communication - The ISAC Technology," 2024 IEEE 2nd International Conference on Sensors, Electronics and Computer Engineering (ICSECE), Jinzhou, China, 2024, pp. 225-229, doi: 10.1109/ICSECE61636.2024.10729432.
12. Hanna Getahun and S. Rajkumar, “Performance analysis of mmWave radio propagations in an indoor environment for 5G networks”, 2023 Eng. Res. Express 5 025075, DOI 10.1088/2631-8695/ac5be7
13. Harsh Tataria, Mansoor Shafi, Mischa Dohler and Shu Sun, “Six Critical Challenges for 6G Wireless Systems”, January 2022, IEEE Vehicular Technology Magazine PP(99):2-12.
14. https://assets.mobileworldlive.com/wp-content/uploads/2021 /02/16115751/Whitepaper-mmWave-5G-Its-crucial-role-in-the-5G-commercial-journey.pdf
15. https://www.coraltechteam.com/design-challenges-in-mmwave-technology/.
16. https://www.dolphmicrowave.com/default/millimeter-wave-propagation-challenges-5-common-issues/
17. J. Zhu, H. Wu, H. Ren, C. Pan and R. Shi, "Fluid/Movable Antenna Meets Active RIS: A Next Generation ISAC System Design," in IEEE Transactions on Network Science and Engineering, vol. 13, pp. 4490-4505, 2026, doi: 10.1109/TNSE.2025.3626520.
18. K. S. Muttair, Oras A. Al-Ani, H. B. Taher, “Designs, developments, challenges, and fabrication materials for MIMO antennas with various 5G and 6G applications: a review”, November 2024, International Journal of Microwave and Wireless Technologies 16(9):1510 - 1539.
19. Li, Yu-Ngok Ruyue et al. “Beam Management in Millimeter-Wave Communications for 5G and Beyond.” IEEE Access 8 (2020): 13282-13293.
20. M. B. Melouka, D. Aissaoui and A. Chaabane, "Reconfigurable Antenna Design for Millimeter-Wave Systems: A Comprehensive Literature Survey," 2024 International

Conference on Telecommunications and Intelligent Systems (ICTIS), Djelfa, Algeria, 2024, pp. 1-5.

21. Muhammad Umar Farooq Qaisar, Weijie Yuan, Onur Günlü, Taneli Riihonen, Yuanhao Cui, Lin Zhang, Nuria Gonzalez Prelcic, Marco Di Renzo, and Zhu Han, "The Role of ISAC in 6G Networks: Enabling Next-Generation Wireless Systems".
22. Qing Xue, Chengwang Ji, Shaodan Ma, Jiajia Guo, Yongjun Xu, Qianbin Chen, Wei Zhang, "A Survey of Beam Management for mmWave and THz Communications Towards 6G", January 2024, IEEE Communications Surveys & Tutorials PP(99):1-1..
23. Rui Xu; Steven Gao; Benito Sanz Izquierdo; Chao Gu; Patrick Reynaert; Alexander Standaert "A Review of Broadband Low-Cost and High-Gain Low-Terahertz Antennas for Wireless Communications Applications", march 2020 IEEE Access PP(99):1-1.
24. Saifullah Khalid, "Artificial-Intelligence-Driven Antenna Design and Optimization: A Comprehensive Review", International Journal of Modeling and Optimization, Vol. 15, No. 2, 2025.
25. Shihao Ju, Yunchou Xing, Ojas Kanhere, Theodore S. Rappaport, "Millimeter Wave and Sub-Terahertz Spatial Statistical Channel Model for an Indoor Office Building", IEEE Journal on selected areas in communications, Vol. 39, no. 6, June 2021.
26. Yasir, "Path Loss at Millimeter Wave Frequencies", January 5, 2019, 5G Fundamentals, https://www.raymaps.com/index.php/path-loss-at-millimeter-wave-frequencies/.