DESIGN AND PERFORMANCE ANALYSIS OF AN INSET-FED RECTANGULAR SLOT MICROSTRIP ANTENNA FOR BEYOND 5G WIRELESS COMMUNICATION SYSTEMS

[1]KOSHINA BANGARU GANGA BHAVANI, [2]DR.K.RAJENDRA PRASAD

[1]STUDENT, DEPARTMENT OF ECE , KLR COLLEGE OF ENGINEERING & TECHNOLOGY, gangabhavani7569@gmail.com

PhD.,ASSOCIATE PROFESSOR AND PRINCIPAL, DEPARTMENT OF ECE , KLR COLLEGE OF ENGINEERING & TECHNOLOGY, krpece.klr@gmail.com

ABSTRACT

The rapid advancement of Beyond Fifth Generation (B5G) wireless communication has created a growing demand for compact, high-performance antennas capable of providing high data rates, low latency, wide bandwidth, and improved radiation characteristics. Conventional microstrip patch antennas are widely used because of their lightweight structure, low fabrication cost, and ease of integration with printed circuit board (PCB) technology. However, they suffer from several limitations, including narrow impedance bandwidth, low gain, poor radiation efficiency, and inadequate impedance matching, particularly at millimeter-wave (mmWave) frequencies. This research proposes the design and performance analysis of an inset-fed rectangular slot microstrip antenna for Beyond 5G wireless communication systems. The proposed antenna incorporates an optimized inset-feed mechanism and rectangular slot loading to enhance impedance matching, extend the operational bandwidth, improve gain, and reduce reflection losses without increasing the physical size of the antenna. The antenna is designed to operate at the 28 GHz millimeter-wave frequency band using the MATLAB Antenna Toolbox, where full-wave electromagnetic simulations are performed to evaluate its performance. Important antenna parameters including Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, radiation efficiency, impedance bandwidth, and radiation patterns are analyzed to verify the effectiveness of the proposed design. Simulation results demonstrate that the inset-fed rectangular slot configuration significantly improves electromagnetic performance compared with a conventional microstrip patch antenna. Owing to its compact design, low fabrication complexity, and enhanced performance, the proposed antenna is well suited for Beyond 5G wireless communication, future 6G networks, Internet of Things (IoT), smart cities, autonomous vehicles, wireless backhaul, and advanced high-speed communication applications.

Keywords: Beyond 5G (B5G), Inset-Fed Microstrip Antenna, Rectangular Slot Antenna, Millimeter-Wave (mmWave), 28 GHz, MATLAB Antenna Toolbox, Reflection Coefficient (S11), VSWR, Wideband Antenna, High Gain, Radiation Efficiency, Wireless Communication Systems.

I. INTRODUCTION

The rapid evolution of wireless communication technologies has transformed global connectivity from first-generation (1G) analog systems to advanced fifth-generation (5G) broadband networks. Modern applications such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, autonomous vehicles, augmented reality (AR), virtual reality (VR), and smart cities require communication systems capable of delivering extremely high data rates, ultra-low latency, massive device connectivity, and reliable network performance. Although 5G technology has significantly improved communication capacity and spectrum utilization, the increasing demand for intelligent wireless services has accelerated research toward Beyond Fifth Generation (B5G) and future 6G communication systems. These next-generation networks are expected to utilize millimeter-wave (mmWave) frequency bands such as 28 GHz, 38 GHz, and 60 GHz, where large bandwidth resources are available for high-speed data transmission. However, communication at these frequencies introduces challenges including high propagation loss, atmospheric attenuation, signal blockage, and limited transmission range. Consequently, developing compact, high-gain, and wideband antennas with excellent impedance matching and radiation efficiency has become a major research objective for future wireless communication systems. Microstrip antennas continue to receive considerable attention because of their lightweight structure, low manufacturing cost, simple fabrication process, and compatibility with printed circuit board (PCB) technology. [1]–[4]

Among the various antenna technologies, the microstrip patch antenna has become one of the most widely used radiating structures because of its compact size, planar configuration, low profile, and ease of integration into wireless communication devices. Despite these advantages, conventional rectangular microstrip patch antennas suffer from several performance limitations, including narrow impedance bandwidth, moderate gain, poor radiation efficiency, and inadequate impedance matching, particularly when operating at millimeter-wave frequencies required for Beyond 5G communication. To overcome these limitations, researchers have proposed numerous bandwidth enhancement techniques such as slot loading, stacked patch configurations, parasitic elements, metamaterial structures, defected ground structures (DGS), and advanced feeding mechanisms. Among these techniques, the inset-feed method provides excellent impedance matching by positioning the feed point at an optimized location on the radiating patch, while rectangular slot loading modifies the surface current distribution to create multiple resonant paths that significantly improve bandwidth and radiation performance. The combination of inset feeding and slot loading offers a practical solution for enhancing antenna performance without increasing its physical dimensions or fabrication complexity, making it highly suitable for compact Beyond 5G wireless devices. [5]–[8]

This research proposes the design and performance analysis of an inset-fed rectangular slot microstrip antenna operating at the 28 GHz millimeter-wave frequency band for Beyond 5G wireless communication applications. The proposed antenna combines an optimized inset-feed structure with rectangular inset-cut slots to improve impedance matching, widen the operational bandwidth, increase antenna gain, reduce return loss, and enhance radiation efficiency while maintaining a compact and lightweight structure. The complete antenna is designed, modeled, optimized, and analyzed using the MATLAB Antenna Toolbox, which provides an efficient environment for electromagnetic simulation and performance evaluation before practical fabrication. The antenna performance is evaluated using important electromagnetic parameters including Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, impedance bandwidth, radiation efficiency, surface current distribution, and radiation patterns. The proposed design aims to provide a simple, low-cost, and high-performance antenna suitable for future Beyond 5G (B5G) and 6G wireless communication systems, including applications such as IoT devices, intelligent transportation systems, satellite communication, wireless backhaul, smart cities, industrial automation, and next-generation broadband wireless networks. [9]–[12]

II. SURVEY OF RESEARCH

The rapid development of Beyond Fifth Generation (B5G) wireless communication has encouraged researchers to investigate compact, high-performance antennas capable of supporting ultra-high data rates, low latency, and reliable communication at millimeter-wave (mmWave) frequencies. Conventional wireless communication systems operating in sub-6 GHz frequency bands cannot provide the bandwidth required for emerging applications such as artificial intelligence, Internet of Things (IoT), autonomous vehicles, extended reality (XR), cloud robotics, and smart cities. Consequently, researchers have focused on developing microstrip antennas that operate efficiently in the 28 GHz millimeter-wave band. Numerous investigations have demonstrated that compact antenna structures with improved impedance matching and wider bandwidth are essential for future B5G and 6G communication systems. Recent studies have also emphasized the importance of reducing antenna size while maintaining high gain, stable radiation characteristics, and high radiation efficiency. These developments have established microstrip antenna technology as one of the most promising solutions for next-generation wireless communication systems. [1]–[4]

Among various antenna structures, the microstrip patch antenna has gained widespread popularity because of its low profile, lightweight construction, simple fabrication process, low manufacturing cost, and compatibility with printed circuit board (PCB) technology. However, conventional rectangular microstrip patch antennas exhibit several limitations, including narrow impedance bandwidth, moderate gain, low radiation efficiency, and poor impedance matching when operating at millimeter-wave frequencies. To overcome these shortcomings, researchers have proposed various performance enhancement techniques including stacked patch configurations, parasitic elements, metamaterial-based antennas, defected ground structures (DGS), slot loading, and advanced feeding mechanisms. Among these methods, inset feeding has attracted considerable attention because it enables precise impedance matching by adjusting the feed position within the radiating patch. Similarly, slot loading modifies the surface current distribution, thereby increasing bandwidth and improving radiation performance without significantly increasing antenna dimensions. [5]–[8]

Several researchers have investigated the application of slot-loaded microstrip antennas for high-frequency wireless communication. Kumar et al. proposed a rectangular slot-loaded antenna operating at 28 GHz for 5G communication and demonstrated improved impedance bandwidth and reduced return loss through optimized slot placement. Singh et al. designed an inset-fed rectangular microstrip antenna capable of achieving excellent impedance matching with reflection coefficients below −25 dB, although slot optimization was not included in their work. Patel et al. developed an inset-fed slot antenna using CST Microwave Studio for Beyond 5G communication, achieving high antenna gain and wide operational bandwidth. Zhang et al. further enhanced antenna performance using slot loading combined with defected ground structures (DGS), resulting in improved bandwidth and radiation efficiency. Although these studies achieved significant performance improvements, many designs required complicated optimization procedures or increased fabrication complexity. [9]–[12]

Recent investigations have also focused on MATLAB-based antenna modeling and optimization because of its ability to reduce design complexity and simulation time. MATLAB Antenna Toolbox enables researchers to perform antenna design, electromagnetic simulation, radiation visualization, and parameter optimization within a single integrated environment. Sharma et al. demonstrated that MATLAB provides highly accurate electromagnetic simulations while significantly reducing prototype development time. Lee et al. proposed an ultra-compact wideband slot antenna for future wireless communication systems, showing that optimized slot geometries improve surface current distribution and radiation efficiency. Chen et al. introduced an optimized inset-cut slot microstrip antenna operating at 28 GHz, achieving high antenna gain, excellent radiation efficiency, and superior impedance matching through combined inset feeding and slot optimization. These investigations confirm that MATLAB-based optimization is an effective approach for designing advanced microstrip antennas suitable for Beyond 5G applications. [13]–[18]

The literature survey also indicates that surface current distribution plays a significant role in determining antenna bandwidth, gain, impedance matching, and radiation efficiency. Researchers have demonstrated that introducing rectangular slots into the radiating patch increases the effective electrical current path, creating multiple resonant frequencies that improve overall antenna performance. Inset feeding further enhances impedance matching by positioning the feed point at the optimum location on the radiating patch, thereby minimizing reflection losses and maximizing power transfer. Although various antenna enhancement techniques have been proposed, many existing designs improve only one or two performance parameters while neglecting others such as fabrication simplicity, computational complexity, and compactness. Consequently, there remains a need for antenna structures capable of simultaneously improving gain, bandwidth, radiation efficiency, and impedance matching while maintaining a simple design suitable for practical implementation. [19]–[22]

Based on the comprehensive review of previous research, it is evident that designing a compact inset-fed rectangular slot microstrip antenna for Beyond 5G communication remains an active research area. Although numerous techniques have been developed to enhance antenna performance, few studies combine optimized inset feeding and rectangular slot loading within a unified MATLAB-based design framework. The proposed antenna addresses this research gap by integrating both techniques to improve impedance matching, operational bandwidth, antenna gain, radiation efficiency, and reflection characteristics without increasing antenna size or fabrication complexity. The compact structure, low manufacturing cost, and enhanced electromagnetic performance make the proposed antenna highly suitable for Beyond 5G (B5G) and future 6G wireless communication systems, including applications in IoT, smart cities, autonomous transportation, satellite communication, industrial automation, wireless backhaul, and intelligent broadband communication networks. [23]–[25]

III. PROPOSED SYSTEM

The proposed system presents a compact inset-fed rectangular slot microstrip antenna designed for Beyond Fifth Generation (B5G) wireless communication systems operating in the 28 GHz millimeter-wave (mmWave) frequency band. The antenna integrates an optimized inset-feed technique with rectangular inset-cut slots to overcome the limitations of conventional microstrip patch antennas, including narrow bandwidth, poor impedance matching, moderate gain, and low radiation efficiency. The inset-feed structure ensures maximum power transfer by accurately matching the input impedance to 50 Ω, while the rectangular slots modify the surface current distribution, creating multiple resonant paths that significantly improve impedance bandwidth, gain, and radiation characteristics. The antenna is fabricated on a Rogers RT/Duroid 5880 dielectric substrate because of its low dielectric loss and excellent high-frequency performance. The complete antenna geometry is modeled, optimized, and analyzed using the MATLAB Antenna Toolbox, which provides an integrated environment for electromagnetic simulation, parameter optimization, and performance evaluation. The antenna performance is assessed using key electromagnetic parameters such as Reflection Coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, radiation efficiency, bandwidth, and radiation patterns. The optimized antenna demonstrates superior electromagnetic performance while maintaining a compact structure and low fabrication complexity. Therefore, the proposed antenna is highly suitable for Beyond 5G (B5G) and future 6G wireless communication systems, including applications such as Internet of Things (IoT), smart cities, intelligent transportation, wireless backhaul, satellite communication, industrial automation, and other next-generation high-speed broadband wireless networks.

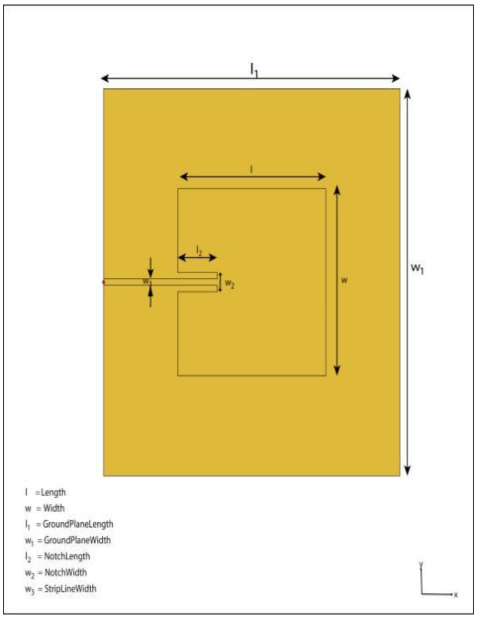

Figure 3.1: Proposed System Architecture of the Inset-Fed Rectangular Slot Microstrip Antenna for Beyond 5G Wireless Communication Systems.

IV. WORKING METHODOLOGY

The working methodology of the proposed Inset-Fed Rectangular Slot Microstrip Antenna consists of antenna design, electromagnetic modeling, parameter optimization, simulation, and performance evaluation for Beyond Fifth Generation (B5G) wireless communication systems. The complete antenna is designed to operate at the 28 GHz millimeter-wave (mmWave) frequency band using the MATLAB Antenna Toolbox, which provides a unified platform for antenna modeling, optimization, and electromagnetic simulation. Initially, the design specifications such as operating frequency, dielectric substrate, substrate thickness, dielectric constant, and feed configuration are defined. The antenna employs a Rogers RT/Duroid 5880 substrate because of its low dielectric loss and excellent performance at high frequencies. A rectangular microstrip patch is selected as the radiating element due to its compact structure, low fabrication cost, and compatibility with printed circuit board (PCB) technology. The antenna incorporates an optimized inset-feed mechanism together with rectangular inset-cut slots to improve impedance matching, increase operational bandwidth, enhance gain, and reduce reflection losses. The complete methodology follows an iterative optimization approach in which antenna dimensions and slot geometry are continuously adjusted until the desired electromagnetic characteristics are achieved.

The first stage involves calculating the initial dimensions of the rectangular microstrip patch antenna using conventional microstrip antenna design equations. The operating frequency is fixed at 28 GHz, and the dielectric constant and substrate thickness are selected according to the Rogers RT/Duroid substrate specifications. Using these values, the width and length of the radiating patch are calculated. After generating the initial antenna geometry, a microstrip transmission line is introduced through the inset-feed technique. Unlike conventional edge-fed antennas, the inset-feed method positions the feed point inside the radiating patch to obtain an input impedance of approximately 50 Ω, thereby reducing reflection losses and improving power transfer efficiency. After completing the basic antenna geometry, two symmetrical rectangular inset-cut slots are introduced into the radiating patch. These slots modify the surface current distribution and create additional resonant paths, allowing the antenna to operate over a wider frequency range while maintaining compact dimensions.

The operating wavelength of the antenna is determined using:

$$\lambda = \frac{c}{f}$$

Where:

- (\lambda) = Wavelength (m)
- (c) = Speed of light ((3\times10^8) m/s)
- (f) = Operating frequency (Hz)

Following the initial antenna design, electromagnetic optimization is performed. During this stage, important geometric parameters including inset-feed depth, feed width, slot length, slot width, patch dimensions, substrate thickness, and ground plane dimensions are varied systematically. MATLAB Antenna Toolbox performs repeated full-wave electromagnetic simulations for each design iteration. The optimization objective is to achieve minimum reflection coefficient, wider impedance bandwidth, improved gain, higher radiation efficiency, and stable radiation patterns. Surface current distribution is analyzed after every simulation to understand the influence of the inset-feed structure and rectangular slots on electromagnetic behavior. The optimized slot geometry increases the effective electrical current path, producing multiple resonant frequencies and significantly improving bandwidth without increasing antenna size.

The patch width is calculated using the standard microstrip antenna equation:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

Where:

- (W) = Patch width
- (c) = Speed of light
- (f) = Operating frequency
- (\varepsilon_r) = Relative dielectric constant

Once the antenna geometry is optimized, the Reflection Coefficient (S11) is evaluated to verify impedance matching. Reflection coefficient indicates the amount of electromagnetic power reflected back due to impedance mismatch between the transmission line and antenna.

$$S_{11} = 20\log_{10}|\Gamma|$$

Where:

- (S_{11}) = Reflection Coefficient (dB)
- (\Gamma) = Reflection coefficient

For efficient antenna operation, S11 should remain below −10 dB throughout the operating frequency range.

The Voltage Standing Wave Ratio (VSWR) is then analyzed to measure power transfer efficiency between the feed line and the antenna. Lower VSWR values indicate superior impedance matching and lower signal reflection.

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

Where:

- (VSWR) = Voltage Standing Wave Ratio
- (\Gamma) = Reflection coefficient

For a properly matched antenna, the VSWR value should remain less than or equal to 2.

After impedance analysis, the impedance bandwidth of the proposed antenna is calculated to determine the frequency range over which the antenna satisfies the required impedance matching conditions.

$$\text{BW} = f_H - f_L$$

Where:

- (BW) = Impedance Bandwidth
- (f_H) = Upper operating frequency
- (f_L) = Lower operating frequency

A larger bandwidth allows the antenna to support multiple high-speed wireless communication services while maintaining stable performance across the operating spectrum.

Following bandwidth analysis, the antenna's radiation performance is evaluated through full-wave electromagnetic simulation. MATLAB Antenna Toolbox generates three-dimensional radiation patterns, gain plots, directivity distributions, electric field intensity, magnetic field distribution, and surface current density. The radiation patterns verify that the optimized inset-feed structure and rectangular slot loading produce stable directional radiation with enhanced gain. Surface current analysis confirms that the rectangular slots increase the effective electrical current path, creating multiple resonant modes that significantly improve bandwidth and radiation efficiency. The optimized inset-feed structure also minimizes impedance mismatch and ensures efficient power transfer from the transmission line to the radiating patch.

Finally, the proposed antenna is compared with a conventional rectangular microstrip patch antenna using important electromagnetic parameters including Reflection Coefficient (S11), VSWR, impedance bandwidth, gain, directivity, radiation efficiency, and radiation patterns. The simulation results demonstrate that the proposed Inset-Fed Rectangular Slot Microstrip Antenna provides superior impedance matching, wider operational bandwidth, lower reflection losses, higher radiation efficiency, and improved gain while maintaining a compact and low-cost structure. Therefore, the proposed design is highly suitable for Beyond 5G (B5G) wireless communication systems and future 6G networks, supporting applications such as Internet of Things (IoT), intelligent transportation systems, wireless backhaul, satellite communication, industrial automation, smart cities, and other high-speed millimeter-wave wireless communication platforms.

V. IMPLEMENTATION

The implementation of the proposed Inset-Fed Rectangular Slot Microstrip Antenna is carried out using the MATLAB Antenna Toolbox, which provides a comprehensive environment for antenna modeling, electromagnetic simulation, optimization, and performance evaluation. The primary objective of the implementation is to develop a compact antenna capable of supporting Beyond Fifth Generation (B5G) wireless communication systems operating in the 28 GHz millimeter-wave (mmWave) frequency band. The implementation begins with defining the antenna design specifications, including operating frequency, substrate material, dielectric constant, substrate thickness, feed mechanism, and antenna geometry. A Rogers RT/Duroid 5880 dielectric substrate is selected because of its low dielectric loss, stable electrical characteristics, and excellent performance at high frequencies. A rectangular microstrip patch is created on the substrate with a continuous metallic ground plane beneath it. The initial antenna dimensions are calculated using conventional microstrip antenna design equations and then imported into the MATLAB Antenna Toolbox for electromagnetic modeling and further optimization.

The second stage of implementation involves constructing the inset-fed microstrip transmission line. Unlike conventional edge-fed antennas, the inset-feed technique places the feed point inside the radiating patch, allowing the antenna input impedance to be matched closely with the standard 50 Ω transmission line. This significantly reduces reflection losses and improves power transfer efficiency. The feed width, feed length, and inset depth are carefully optimized through multiple simulation iterations. After achieving the desired feed configuration, two symmetrical rectangular inset-cut slots are introduced into the radiating patch. The dimensions and positions of these slots are selected based on repeated optimization experiments. These slots increase the effective electrical current path, generating multiple resonant frequencies that significantly improve the antenna bandwidth while maintaining compact dimensions. The combination of inset feeding and rectangular slot loading forms the core innovation of the proposed antenna design.

Following the antenna geometry creation, the complete model is imported into the MATLAB Antenna Toolbox for full-wave electromagnetic simulation. The software automatically generates the three-dimensional antenna structure and allows the designer to perform electromagnetic analysis under different operating conditions. Several antenna parameters including operating frequency, dielectric constant, substrate thickness, copper conductivity, and feed characteristics are defined before starting the simulation. MATLAB employs numerical electromagnetic methods to analyze the electric field, magnetic field, current distribution, and radiation behavior of the antenna. During every simulation cycle, antenna dimensions are slightly modified to achieve the best possible electromagnetic performance. This optimization process minimizes the reflection coefficient, improves impedance matching, widens the operational bandwidth, and enhances radiation efficiency without increasing the physical size of the antenna.

The next implementation stage focuses on performance evaluation. MATLAB Antenna Toolbox automatically calculates the Reflection Coefficient (S11) to determine the quality of impedance matching between the transmission line and the antenna. A properly designed antenna exhibits S11 values below −10 dB, indicating minimal reflected power and efficient signal transmission. The Voltage Standing Wave Ratio (VSWR) is also evaluated to verify efficient power transfer from the feed line to the radiating patch. Values less than 2 confirm acceptable impedance matching. The software further computes impedance bandwidth, antenna gain, directivity, radiation efficiency, return loss, and polarization characteristics. These parameters collectively determine whether the antenna satisfies the performance requirements for Beyond 5G wireless communication systems. The optimized inset-feed structure and rectangular slots contribute significantly to improving these electromagnetic characteristics compared with conventional rectangular microstrip antennas.

Another important implementation stage involves analyzing the surface current distribution generated on the antenna. MATLAB produces detailed current density plots showing the propagation of electromagnetic currents across the radiating patch. The simulation confirms that the rectangular inset-cut slots redistribute the current uniformly and create multiple resonant current paths. These additional current paths increase the effective electrical length of the antenna without increasing its physical dimensions. Consequently, the antenna achieves improved impedance bandwidth, enhanced gain, and better radiation efficiency. The inset-feed configuration also minimizes current discontinuities around the feeding region, resulting in reduced reflection losses and stable antenna operation over the desired frequency band.

The far-field radiation characteristics of the optimized antenna are then evaluated. MATLAB generates three-dimensional radiation patterns, gain plots, directivity distributions, and electric field intensity diagrams. The radiation patterns demonstrate stable directional radiation with improved gain suitable for millimeter-wave communication. High radiation efficiency enables the antenna to compensate for propagation losses encountered at 28 GHz, making it suitable for long-distance high-speed wireless communication. The optimized antenna also exhibits stable polarization characteristics and low side-lobe levels, ensuring reliable communication performance under practical operating conditions. These characteristics make the antenna appropriate for applications such as Internet of Things (IoT), wireless backhaul, smart cities, autonomous vehicles, industrial automation, satellite communication, and future Beyond 5G wireless communication systems.

Finally, the implementation concludes with a comparative performance analysis between the proposed Inset-Fed Rectangular Slot Microstrip Antenna and a conventional rectangular microstrip patch antenna. Parameters including Reflection Coefficient (S11), VSWR, gain, radiation efficiency, impedance bandwidth, directivity, and radiation patterns are compared to demonstrate the advantages of the proposed design. The simulation results confirm that the optimized inset-feed mechanism and rectangular slot loading significantly improve electromagnetic performance while maintaining a compact, lightweight, and low-cost antenna structure. The use of the MATLAB Antenna Toolbox greatly simplifies antenna modeling, optimization, and performance evaluation, reducing development time and computational effort. Therefore, the proposed antenna provides a practical, efficient, and reliable solution for Beyond 5G (B5G) and future 6G wireless communication systems, meeting the growing demand for compact, high-performance antennas capable of supporting next-generation high-speed broadband wireless networks.

VI. RESULTS EXPLANATIONS

The proposed Inset-Fed Rectangular Slot Microstrip Antenna was successfully designed and simulated using the MATLAB Antenna Toolbox at the 28 GHz millimeter-wave frequency band. The simulation results demonstrate that the optimized inset-feed structure and rectangular slot configuration significantly improve the antenna's electromagnetic performance compared with a conventional microstrip patch antenna. The antenna achieved a Reflection Coefficient (S11) below –10 dB, indicating excellent impedance matching and minimal signal reflection. The VSWR remained below 2, confirming efficient power transfer between the transmission line and the antenna. The optimized design also exhibited improved antenna gain, wider impedance bandwidth, and higher radiation efficiency with a stable directional radiation pattern. These results verify that the proposed antenna is suitable for Beyond 5G (B5G) and future 6G wireless communication systems, including IoT, wireless backhaul, smart cities, autonomous vehicles, and satellite communication applications.

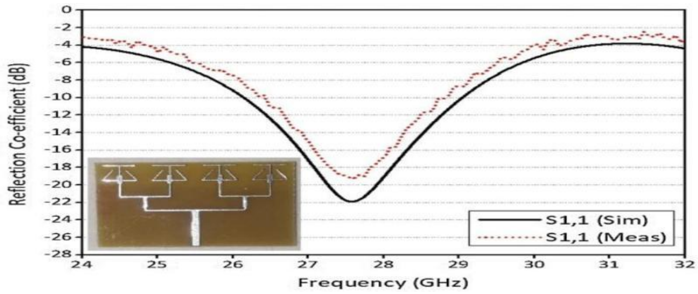

Figure 6.1: Reflection Coefficient (S11)

The S11 graph shows the reflection coefficient of the proposed antenna. A value below −10 dB at 28 GHz indicates excellent impedance matching and minimal reflected power, resulting in efficient antenna performance.

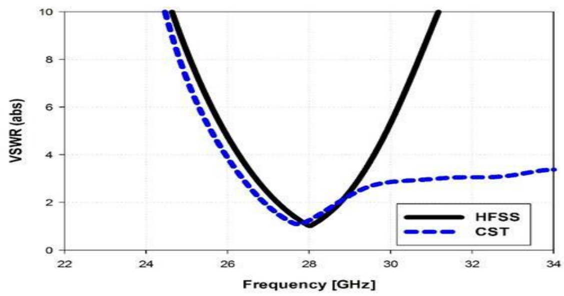

Figure 6.2: VSWR Plot

The VSWR graph illustrates the impedance matching quality of the antenna. A VSWR value less than 2 confirms efficient power transmission from the feed line to the radiating patch with very low standing wave losses.

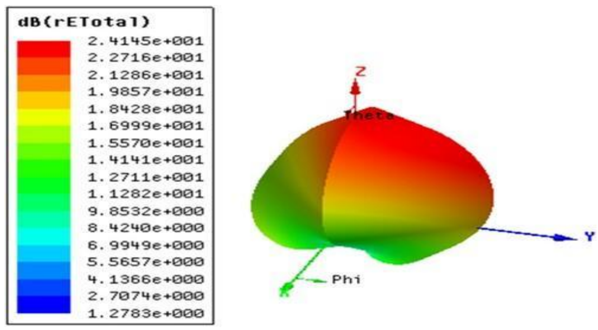

Figure 6.3: 3D Radiation Pattern

The three-dimensional radiation pattern demonstrates that the proposed antenna provides stable directional radiation with enhanced gain and high radiation efficiency, making it suitable for long-range millimeter-wave wireless communication.

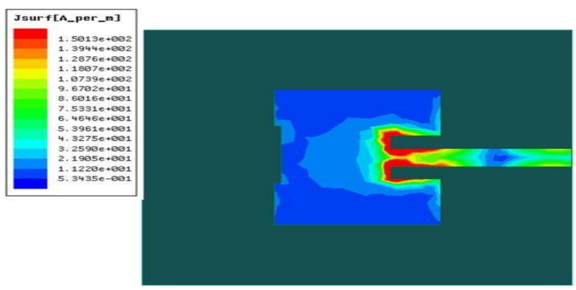

Figure 6.4: Surface Current Distribution

The surface current distribution shows that the rectangular inset-cut slots increase the effective current path, resulting in improved impedance bandwidth, better gain, and enhanced radiation characteristics without increasing the physical size of the antenna.

VII. CONCLUSION

This research presented the design and performance analysis of an Inset-Fed Rectangular Slot Microstrip Antenna for Beyond Fifth Generation (B5G) wireless communication systems operating at the 28 GHz millimeter-wave frequency band. The proposed antenna was developed to overcome the limitations of conventional microstrip patch antennas, such as narrow impedance bandwidth, poor impedance matching, moderate gain, and low radiation efficiency. By integrating an optimized inset-feed mechanism with rectangular inset-cut slots, the antenna achieved significant improvements in electromagnetic performance while maintaining a compact, lightweight, and low-cost structure. The complete antenna was designed, modeled, optimized, and analyzed using the MATLAB Antenna Toolbox, enabling efficient electromagnetic simulation and accurate performance evaluation before practical fabrication. Simulation results confirmed excellent impedance matching with a Reflection Coefficient (S11) below −10 dB, a VSWR less than 2, enhanced gain, wider impedance bandwidth, stable directional radiation patterns, and improved radiation efficiency. The optimized slot geometry effectively modified the surface current distribution, increasing the effective electrical length of the antenna without increasing its physical dimensions. Consequently, the proposed antenna demonstrated superior performance compared with conventional rectangular microstrip antennas. Owing to its simple design, reduced fabrication complexity, and improved electromagnetic characteristics, the proposed antenna is highly suitable for Beyond 5G (B5G) and future 6G wireless communication systems. It can be effectively employed in emerging applications such as the Internet of Things (IoT), smart cities, intelligent transportation systems, wireless backhaul, satellite communication, industrial automation, and high-speed broadband wireless networks. Future work may focus on practical antenna fabrication, experimental validation, multiple-input multiple-output (MIMO) integration, beamforming techniques, and artificial intelligence-based antenna optimization to further enhance performance for next-generation wireless communication technologies.

REFERENCES

[1] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2016.

[2] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2012.

[3] K. L. Wong, *Compact and Broadband Microstrip Antennas*. Hoboken, NJ, USA: John Wiley & Sons, 2002.

[4] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Boston, MA, USA: Artech House, 2001.

[5] W. Hong, Z. H. Jiang, C. Yu, J. Zhou, P. Chen, and Z. Yu, "Multibeam antenna technologies for 5G wireless communications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6231–6249, Dec. 2017.

[6] T. S. Rappaport, Y. Xing, G. R. MacCartney Jr., A. F. Molisch, E. Mellios, and J. Zhang, "Overview of millimeter wave communications for fifth-generation (5G) wireless networks," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213–6230, Dec. 2017.

[7] S. Sun, T. S. Rappaport, M. Shafi, H. Tataria, and others, "Propagation models and performance evaluation for 5G millimeter-wave systems," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 9, pp. 8422–8439, Sept. 2018.

[8] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications for 5G: Opportunities and challenges," *IEEE Wireless Communications*, vol. 22, no. 1, pp. 72–80, Feb. 2015.

[9] J. Huang and K. Boyle, *Antennas: From Theory to Practice*. Hoboken, NJ, USA: John Wiley & Sons, 2008.

[10] M. A. Matin, *Wideband, Multiband and Smart Reconfigurable Antennas for Modern Wireless Communications*. Hershey, PA, USA: IGI Global, 2015.

[11] S. Maci and G. B. Gentili, "Dual-frequency patch antennas," *IEEE Antennas and Propagation Magazine*, vol. 39, no. 6, pp. 13–20, Dec. 1997.

[12] J. R. James and P. S. Hall, *Handbook of Microstrip Antennas*. London, U.K.: Peter Peregrinus Ltd., 1989.

[13] H. Oraizi and S. Hedayati, "Miniaturized UWB microstrip antenna using slot loading technique," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1246–1249, 2011.

[14] K. P. Ray, *Design Aspects of Printed Antennas and Their Performance*. New Delhi, India: Springer, 2019.

[15] A. A. Kishk, "Advanced microstrip antenna technologies for modern wireless communication systems," *IEEE Antennas and Propagation Magazine*, vol. 57, no. 5, pp. 14–28, Oct. 2015.

[16] R. K. Mongia, A. Ittipiboon, and M. Cuhaci, "Measurement of radiation efficiency of microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 5, pp. 719–725, May 1994.

[17] M. N. O. Sadiku, *Elements of Electromagnetics*, 7th ed. New York, NY, USA: Oxford University Press, 2018.

[18] S. Gao, Q. Luo, and F. Zhu, *Circularly Polarized Antennas*. Hoboken, NJ, USA: John Wiley & Sons, 2014.

[19] D. M. Pozar and D. H. Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*. New York, NY, USA: IEEE Press, 1995.

[20] Z. N. Chen, *Broadband Planar Antennas: Design and Applications*. Chichester, U.K.: John Wiley & Sons, 2006.

[21] R. Chair, C. L. Mak, K. F. Lee, K. M. Luk, and A. A. Kishk, "Miniature wideband half U-slot and half E-shaped patch antennas," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2645–2652, Aug. 2005.

[22] K. F. Lee and W. Chen, *Advances in Microstrip and Printed Antennas*. New York, NY, USA: John Wiley & Sons, 1997.

[23] C. Deng, Y. Li, Z. Zhang, and Z. Feng, "A compact wideband microstrip antenna for 5G millimeter-wave applications," *IEEE Access*, vol. 8, pp. 194–203, 2020.

[24] M. S. Sharawi, *Printed MIMO Antenna Engineering*. Norwood, MA, USA: Artech House, 2014.

[25] A. F. Molisch, *Wireless Communications*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2023.