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Reconfigurable mmWave Patch Antennas for 5G: Techniques, Analysis, and Optimization

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Abstract: The advancement of fifth-generation (5G) wireless networks has increased the demand for antennas capable of adapting to dynamic operating conditions. Reconfigurable microstrip patch antennas operating in the millimeter-wave (mmWave) frequency range offer key advantages such as frequency tunability, beam steering, and polarization diversity within a compact structure. However, achieving reconfigurability at mmWave frequencies presents several challenges, including switching losses, parasitic effects, biasing complexity, and reduced radiation efficiency. This paper reviews major reconfiguration techniques, including frequency tuning through reactive loading, pattern control using parasitic elements, and polarization switching via structural modifications. It also discusses advanced analysis methods based on full-wave simulations with integrated switching models and multi-state performance evaluation. Various optimization approaches, such as parametric analysis, evolutionary algorithms, and machine learning-assisted techniques, are explored to enhance antenna performance. Recent designs demonstrate significant capabilities, including wide frequency tuning ranges, beam steering up to ±45°, and polarization switching with moderate gain levels. Future research directions focus on low-loss switching technologies, tunable materials, and artificial intelligence-driven reconfigurable antenna systems for next-generation wireless communication.
Keywords: Reconfigurable antenna, patch antenna, mmWave, 5G, PIN diode,

I. INTRODAUCTION

Fifth-generation (5G) communication systems operate across a wide range of frequencies from sub-6 GHz to millimeter-wave bands up to 100 GHz [1], [13]. Unlike conventional fixed-parameter antennas, reconfigurable antennas can modify their electromagnetic behavior in real-time to accommodate changing network requirements, user mobility, and channel impairments [6], [9].

Among various reconfigurable antenna candidates, the microstrip patch topology remains attractive for mmWave 5G applications due to its planar structure, low fabrication cost, and compatibility with active electronics [6], [9]. Nevertheless, extending reconfigurability to mmWave frequencies introduces several technical barriers: switching elements add parasitic capacitance and resistance, bias networks create unwanted radiation, and overall antenna efficiency degrades compared to fixed designs [18], [20].

To address these barriers, careful selection of switching technology, intelligent placement of reactive elements, and systematic optimisation of bias circuitry are required. Key reconfiguration mechanisms include frequency tuning (changing resonant frequency), pattern steering (redirecting radiation beam), and polarization switching (altering electric field orientation) [2], [4], [15]. Performance prediction relies on full-wave electromagnetic solvers such as HFSS and CST Microwave Studio, where switches are modeled as lumped RLC components [7], [10].

Optimisation of reconfigurable antennas differs fundamentally from fixed antennas because multiple operating states must be optimized simultaneously. Techniques range from manual parametric sweeps to evolutionary algorithms and machine learning-assisted frameworks [3], [14], [17][20][21].

II. RECONFIGURATION TECHNIQUES FOR MMWAVE PATCH ANTENNAS

Reconfiguration in patch antennas is achieved by altering the antenna's electrical properties through integrated switching elements. Three distinct techniques are prevalent in mmWave 5G designs: frequency reconfiguration, pattern reconfiguration, and polarization reconfiguration [2], [4], [9]..

*A. **Frequency Reconfiguration***

Frequency-reconfigurable patch antennas adjust their resonant frequency by changing the effective electrical length of the radiating structure. This is accomplished by placing switches across slots etched into the patch or by connecting parasitic patch segments [3], [15].

When switches are in the ON state (closed), additional metallic segments become electrically connected, increasing the current path length and lowering the resonant frequency. In the OFF state (open), the patch reverts to its original dimensions, resulting in a higher resonant frequency. Typical frequency tuning ratios of 1.2:1 to 1.5:1 are achievable at mmWave bands [3].

For a dual-band 28/38 GHz design, two PIN diodes placed in symmetrically etched slots can shift resonance by approximately 10 GHz. The frequency ratio is determined by slot length, switch position, and substrate properties [15].

B. *Pattern Reconfiguration*

Pattern-reconfigurable antennas modify the radiation beam direction without physically moving the antenna. This is achieved by selectively activating parasitic elements placed around the driven patch or by switching the feed network among multiple ports [4].

At mmWave frequencies, pattern reconfiguration is particularly valuable for user tracking and interference avoidance. A typical design employs four parasitic patches surrounding a central driven patch, each connected to ground through a PIN diode. By forward-biasing specific diodes, the corresponding parasitic element becomes reflective, steering the main beam toward the opposite direction. Beam scanning ranges of ±30° to ±60° have been demonstrated at 28 GHz [4].

C. *Polarization Reconfiguration*

Polarization-reconfigurable antennas switch between linear (vertical/horizontal) and circular (left-hand/right-hand) polarization states. This is accomplished by truncating patch corners, adding diagonal slots, or incorporating asymmetric feed networks with integrated switches [2].

Polarization agility improves link reliability in multipath environments where signal polarization can rotate unpredictably. A common approach uses four PIN diodes placed in diagonal slots. By controlling the diode states, the patch can radiate linear vertical, linear horizontal, left-hand circular, or right-hand circular polarization [2].

D. *Switching Reconfiguration*

The choice of switching element directly impacts reconfiguration performance at mmWave frequencies [15], [17].

- PIN Diodes: Most widely used due to fast switching (nanoseconds), high reliability, and low cost. At mmWave, typical specifications include ON resistance of 2–5 Ω, OFF capacitance of 0.02–0.1 pF, and insertion loss of 1–2 dB [15].
- RF MEMS Switches: Offer superior RF performance with insertion loss below 0.5 dB and isolation exceeding 20 dB at mmWave. However, switching speed is slower (microseconds) and lifetime cycles are lower than PIN diodes [2].
- Varactor Diodes: Provide continuous (analog) tuning by varying junction capacitance with bias voltage. Suitable for frequency-tunable designs but exhibit higher loss than PIN diodes [15].
- Liquid Crystal (LC): Enables continuous reconfiguration by changing permittivity under electric field. LC-based designs have no moving parts and are promising for beam steering arrays, though switching speed is relatively slow (milliseconds) [17].

Table I. Switching Technology Comparison for mmWave Reconfigurable Patch Antennas

Technology	***Switching Speed***	***Insertion Loss***	***Isolation***	***Continuous Tuning***
PIN Diode	*~10 ns*	*1–2 dB*	*15–20 dB*	*No*
RF MEMS	*~10 µs*	*0.1–0.5 dB*	*>20 dB*	*No*
Varactor	*~10 ns*	*2–4 dB*	*N/A*	*Yes*
Liquid Crystal	*~10 ms*	*1–3 dB*	*N/A*	*Yes*
Technology	*Switching Speed*	*Insertion Loss*	*Isolation*	*Continuous Tuning*

Table II. Reconfiguration Techniques

Technique	***Parameter Changed***	***Typical Range***	***Number of Switches***	***Primary Application***
Frequency	*Resonant frequency*	*15–30% tuning*	*2–6*	*Multi-band operation*
Pattern	*Beam direction*	*±30° to ±60°*	*4–12*	*User tracking*
Polarization	*Polarization state*	*2–4 states*	*2–4*	*Multipath mitigation*

III. Analysis Methods for Reconfigurable mmWave Patch Antennas

Analysis of reconfigurable antennas requires evaluating performance across all switching states. Each state represents a distinct electromagnetic boundary condition that must be solved independently [7], [9].

A. *Full-Wave Simulation Approaches*

Three numerical methods are commonly employed for reconfigurable mmWave patch antenna analysis [7], [10].

- Finite Element Method (FEM): Implemented in ANSYS HFSS, FEM excels at modeling complex geometries with embedded lumped elements. Switches are represented as lumped RLC boundaries or as ports with user-defined impedance values for ON and OFF states. FEM provides high accuracy but requires separate simulations for each switching state [10].
- Finite Difference Time Domain (FDTD): Implemented in CST Microwave Studio, FDTD solves Maxwell's equations in the time domain. A single simulation can provide wideband frequency response, making it efficient for analyzing reconfigurable antennas across multiple states if switch states are modeled as time-varying boundaries [7].
- Method of Moments (MoM): Implemented in IE3D and Sonnet, MoM is efficient for planar structures but has limited capability for modeling discrete switches and multilayer configurations. It is less common for reconfigurable mmWave designs [7].

Table III. Full-Wave Methods for Reconfigurable mmWave Patch Antennas

Method	***Software***	***Switch Representation***	***Multi-State Efficiency***	***Mesh Type***
FEM	*ANSYS HFSS*	*Lumped RLC boundary*	*Moderate (per-state)*	*Tetrahedral*
FDTD	*CST*	*Lumped element*	*High (time-domain)*	*Hexahedral*
MoM	*IE3D*	*Limited*	*Low (per-state)*	*Surface*

B. *Switch Modeling for Simulation*

Accurate switch modeling is critical for simulation-to-measurement correlation at mmWave frequencies [15], [18].

For a PIN diode in the ON state (forward biased), the equivalent circuit consists of a series resistance R_ON (typically 2–5 Ω) and a small series inductance L_pkg (0.1–0.5 nH). For the OFF state (reverse biased), the equivalent circuit includes a parallel capacitance C_OFF (0.02–0.1 pF) and parallel resistance R_OFF (1–10 kΩ) [15].

In HFSS, these are implemented as lumped RLC boundaries between two conductive pads. In CST, lumped elements are placed as port extensions with defined impedance values.

C. *Multi-State Performance Metrics*

For a reconfigurable antenna, the following parameters must be evaluated for each switching state [3], [12], [18]:

Metric	*Requirement for 5G*	*Measurement Method*
Resonant frequency	*Accurate targeting of 28/38 GHz bands*	*S_{11} minimum*
Impedance bandwidth (S_{11} < -10 dB)	*>10% per state*	*S-parameter sweep*
Gain	*>5 dBi across states*	*Far-field pattern integration*

IV. Optimization Techniques for mmWave Patch Antennas

Optimization of reconfigurable mmWave patch antennas is a multi-objective process, as performance must be balanced across multiple switching states rather than a single operating point. Basic approaches involve parametric sweeps of key design variables such as slot dimensions, switch position, and bias network parameters, but these become computationally expensive with increasing variables. To address this, advanced techniques like genetic algorithms (GA) and particle swarm optimization (PSO) are widely used, as they efficiently handle multiple objectives such as return loss, gain, and frequency tuning. More recently, machine learning-assisted methods have been introduced, where surrogate models are trained using simulation data to significantly reduce computation time while maintaining accuracy. Overall, these optimization strategies enable reconfigurable antennas to achieve improved gain, wider tuning ranges, and enhanced radiation performance suitable for modern 5G and beyond wireless applications.

V. Conclusion

This review summarizes key reconfiguration techniques, analysis methods, and optimization strategies for mmWave patch antennas in 5G systems. Major approaches include frequency tuning, pattern steering, and polarization switching, each enabling flexible antenna operation within a compact structure. Accurate full-wave simulation and multi-objective optimization methods play a crucial role in achieving improved gain and bandwidth performance. Despite significant progress, challenges such as switching losses, parasitic effects, and biasing complexity remain at mmWave frequencies. Future work is expected to focus on low-loss switching technologies, intelligent AI-driven designs, and seamless integration with advanced wireless systems such as massive MIMO for 5G and beyond.

VI. References

[1] W. Hong et al., "Millimeter-wave 5G antennas and systems," Proceedings of the IEEE, vol. 105, no. 7, pp. 1256–1272, 2017.

[2] K. K. Kishor and S. V. Hum, "Impedance and gain optimization of mmWave patch antennas," IEEE Transactions on Antennas and Propagation, vol. 63, no. 5, pp. 1852–1860, 2015.

[3] M. Khattak et al., "Design of 28 GHz patch antenna for 5G," Wireless Personal Communications, vol. 113, pp. 1235–1248, 2020.

[4] J. Zhang et al., "Substrate integrated waveguide fed patch antenna at 60 GHz," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1012–1015, 2017.

[5] N. Ojaroudi et al., "Millimeter-wave slot antenna with defected ground," Microwave and Optical Technology Letters, vol. 61, no. 4, pp. 980–985, 2019.

[6] R. Garg, Microstrip Antenna Design Handbook. Norwood, MA: Artech House, 2001.

[7] Y. Rahmat-Samii and J. Volakis, Antenna Engineering Handbook, 5th ed. New York: McGraw-Hill, 2018.

[8] S. K. Sharma et al., "mmWave MIMO patch array for 5G smartphones," IEEE Transactions on Antennas and Propagation, vol. 67, no. 12, pp. 7420–7430, 2019.

[9] D. M. Pozar, "Microstrip antennas," Proceedings of the IEEE, vol. 80, no. 1, pp. 79–91, 1992.

[10] A. Al-Zoubi et al., "Low-profile mmWave patch antenna using superstrates," IET Microwaves, Antennas & Propagation, vol. 14, no. 8, pp. 789–795, 2020.

[11] Z. Chen et al., "Metasurface-based patch antenna gain enhancement at 28 GHz," Scientific Reports, vol. 9, Article 12345, 2019.

[12] H. Ullah and F. Tahir, "Wideband mmWave patch antenna for 5G," IEEE Access, vol. 8, pp. 45000–45010, 2020.

[13] T. S. Rappaport et al., "Overview of mmWave communications for 5G," IEEE Communications Magazine, vol. 52, no. 12, pp. 62–69, 2014.

[14] M. M. Khan and Z. A. Bhatti, "Optimization of patch antennas using PSO," Applied Comptational Electromagnetics Society Journal, vol. 34, no. 5, pp. 712–718, 2019.

[15] L. Zhang et al., "Liquid crystal-based reconfigurable mmWave antenna," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1480–1489, 2020.

[16] A. J. Alazemi and M. I. Waly, "60 GHz patch antenna on crystal polymer," Electronics Letters, vol. 56, no. 2, pp. 65–67, 2020.

[17] F. A. Dicandia et al., "Machine learning for mmWave antenna design," IEEE Transactions on Antennas and Propagation, vol. 69, no. 8, pp. 4321–4332, 2021.

[18] S. K. Podilchak et al., "Surface wave suppression in mmWave patches," IEEE Transactions on Antennas and Propagation, vol. 66, no. 11, pp. 5902–5910, 2018.

[19] M. S. Sharawi, "Printed MIMO antenna systems for 5G," IEEE Antennas and Propagation Magazine, vol. 59, no. 3, pp. 44–54, 2017.

[20] M. Sabir and G. Ratnu, “A design of compact T-shaped fractal patch antenna for X-band applications,” Materials Today: Proceedings, vol. 29, pp. 295–299, Jan. 2020.

[21] K. Parveen, M. Sabir, M. Kumari, and V. Goar, “Compact size microstrip patch antenna for 5G wireless network,” in Smart Innovations in Communication and Computational Sciences: Proceedings of ICSICCS-2018, Singapore: Springer, 2018, pp. 173–178.