

Wideband and High-Gain Multimode Microstrip Antenna for 3.5 GHz 5G Applications

F. S. Borges, T. C. Pimenta, G. L. F. Brandão, and R. A. Santos

Abstract—This paper presents a wideband and high-gain microstrip patch antenna operating at 3.5 GHz for sub-6 GHz 5G applications. The proposed structure employs shorting vias to enable the controlled coupling of TM_{03} -like and TM_{11} -like modes, producing a dual-resonance response for bandwidth enhancement. Simulated results show a 14.6% bandwidth (3.29–3.81 GHz) and realized gain up to 9.6 dBi. Measurements confirm a 16.0% bandwidth (3.27–3.84 GHz) while simulations show stable broadside radiation. The results demonstrate an efficient low-profile antenna with enhanced bandwidth, high gain, and simple structure for sub-6 GHz 5G systems.

Keywords—5G communications, higher-order modes, microstrip patch antenna, multimode operation, wideband antennas.

I. INTRODUCTION

The increasing demand for higher data rates and spectral efficiency in fifth-generation (5G) wireless systems has intensified the need for antennas combining wide bandwidth, high gain, and stable radiation characteristics. In this context, antenna performance directly impacts coverage, link reliability, and communication capacity, making compact and efficient radiating structures essential for sub-6 GHz 5G applications [1], [2].

In Brazil, the 3.3 to 3.8 GHz band has been allocated for sub-6 GHz 5G systems [3], [4]. This frequency range requires antennas capable of covering the entire operating band while maintaining proper impedance matching, stable radiation characteristics, and high gain. Consequently, wideband antenna designs have become essential for modern 5G applications.

Among the available radiating technologies, microstrip patch antennas (MPAs) are attractive for sub-6 GHz 5G systems due to their low profile, compact structure, low fabrication cost, and easy integration with printed circuits [5], [6]. However, conventional MPAs operating in the fundamental TM_{10} mode typically exhibit narrow bandwidth and moderate gain. The limited bandwidth is mainly associated with the high quality factor (Q) of the resonant cavity, which results in a highly selective frequency response. In addition, the gain is restricted by the reduced effective radiating area of the patch, which limits the achievable directivity.

To overcome these limitations while preserving the advantages of MPAs, several bandwidth and gain enhancement

techniques have been investigated. Among them, modal engineering has emerged as an effective approach based on the controlled excitation of higher-order resonant modes, which increases the effective electrical size of the radiator. Recent works have demonstrated that the combination of higher-order modes can significantly improve bandwidth and gain performance through techniques such as slots, shorting vias, and parasitic structures [7], [8], [9].

Within this context, this paper proposes a wideband and high-gain MPA operating at 3.5 GHz based on the controlled coupling of TM_{03} -like and TM_{11} -like modes in a single planar structure. The proposed antenna employs shorting vias to modify the cavity boundary conditions and produce a dual-resonance response, enabling bandwidth enhancement while maintaining stable broadside radiation. As a result, the antenna fully covers the licensed 3.3 to 3.8 GHz 5G band, achieving a simulated bandwidth of 14.6% and realized gain ranging from 7.2 to 9.6 dBi.

To validate the proposed multimode approach, the remainder of this paper is organized as follows. Section II presents the antenna configuration and discusses its operation mechanism. Section III provides the numerical and experimental results. Finally, Section IV summarizes the main conclusions of this work.

II. DESIGN AND ANALYSIS

A. Design geometry

Figure 1 presents the conventional and proposed antenna configurations, while the optimized dimensions are summarized in Table I. Both structures are centered at (0, 0) on the xy -plane and use a $50\ \Omega$ coaxial probe feed placed at a distance d from the patch edge to provide impedance matching. The antennas were implemented on an Arlon DiClad 870 substrate with $\epsilon_r = 2.33 \pm 0.02$, $\tan(\delta) = 0.0013$, and thickness $h = 3.18$ mm.

Model 1 consists of a conventional rectangular MPA operating in the fundamental TM_{10} mode. Based on this reference structure, Model 2 introduces metallic shorting vias connecting

TABLE I: Geometrical dimensions of the proposed MPAs.

Models	Parameters [mm]							
	L	W	L_d	W_d	d	h	p	r
Model 1	24.5	70	60	76.5	1.6	3.18	–	–
Model 2	24.5	95.5	60	105	3.3	3.18	2.2	0.6

F. S. Borges and T. C. Pimenta are with the Institute of Engineering, Systems and Information Technologies (IESTI), Federal University of Itajubá, Itajubá, MG, Brazil, e-mail: {d2021103291, tales}@unifei.edu.br.

G. L. F. Brandão and R. A. Santos are with the School of Electrical Engineering (FEELT), Federal University of Uberlândia, Patos de Minas Campus, Patos de Minas, MG, Brazil, e-mail: {guilherme.brandao, renans}@ufu.br.

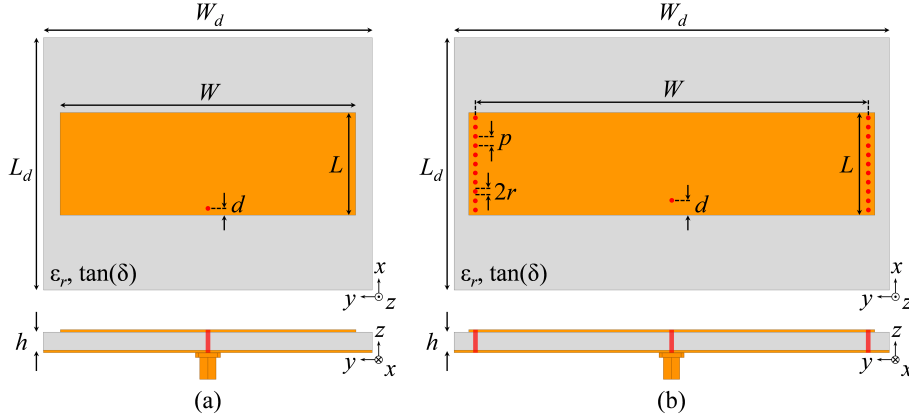


Fig. 1: Geometry of the proposed microstrip patch antennas. (a) Conventional antenna (Model 1). (b) Proposed multimode antenna with shorting vias (Model 2).

the patch to the ground plane. These vias, characterized by radius r and spacing p , modify cavity boundary conditions and enable controlled excitation of higher-order resonant modes.

B. Working principle

Model 1 consists of a rectangular MPA with an electrically large width W , operating in the fundamental TM_{10} mode at $f_r \approx 3.58$ GHz. The electric field distribution shown in Fig. 2(b) confirms this operating mode, exhibiting a half-cycle field variation along the dimension L and negligible variation along W . As illustrated in Fig. 2(a), the antenna presents an impedance bandwidth from 3.41 to 3.67 GHz for $|S_{11}| \leq -10$ dB, corresponding to a fractional bandwidth of 7.3%. Over this frequency range, the realized gain (G_R) varies from 8.51 (3.41 GHz) to 8.91 dBi (3.67 GHz), reaching a maximum value of 9.23 dBi near the resonant frequency.

It is worth noting that Model 1 exhibits relatively high bandwidth and realized gain for a MPA operating in the TM_{10} mode. The bandwidth enhancement is mainly associated with the thick dielectric substrate, which reduces the cavity quality factor and increases the radiative coupling at the patch edges [10]. Meanwhile, the high realized gain is attributed to the electrically large width W , which enlarges the effective radiating area and improves the broadside directivity [11].

Although Model 1 provides high realized gain, its bandwidth is insufficient to fully cover the allocated 3.3 to 3.8 GHz 5G band. Therefore, Model 2 is proposed to enhance the impedance bandwidth while maintaining high gain, stable broadside radiation, and a simple single-layer structure.

To achieve this objective, Model 2 incorporates metallic shorting vias along two patch edges, creating approximate electric walls while preserving the opposite edges as radiating apertures. This modification changes the cavity boundary conditions and enables the excitation of higher-order resonant modes. Under this interpretation, the resonant frequencies can be estimated using the rectangular cavity model with effective dimensions [8]:

$$f_{\text{TM}_{mn}} \approx \frac{3 \times 10^8}{2\pi\sqrt{\epsilon_r}} \sqrt{\left(\frac{m\pi}{L_e}\right)^2 + \left(\frac{n\pi}{W_e}\right)^2} \quad (1)$$

where W_e and L_e are given by:

$$W_e = W - \frac{(2r)^2}{0.95p} \quad (2)$$

$$L_e = L + 2\Delta L \quad (3)$$

with ΔL representing the fringing-field extension at the radiating edges [12].

Due to the modified boundary conditions imposed by the vias, the excited modes are referred to as TM_{11} -like and TM_{03} -like modes. The bandwidth enhancement results from the controlled coupling between these resonances, whose frequency spacing is mainly governed by the ratio W/L . Figure 3(a) presents the parametric analysis for fixed $L \approx 24.5$ mm and varying W , showing good agreement between the analytical model and HFSS simulations. It can be observed that the TM_{03} -like mode is more sensitive to variations in W/L , allowing the resonance spacing to be adjusted through a single geometric parameter.

Figure 3(b) presents the simulated reflection coefficient for different values of W/L , while Table II summarizes the corresponding bandwidth variation. As W/L increases, the TM_{03} -like resonance shifts toward lower frequencies while the TM_{11} -like resonance remains nearly fixed, increasing the frequency spacing between the two resonances and widening the impedance bandwidth. Consequently, the fractional bandwidth increases from 12.81% for $W/L = 3.8$ to 15.04% for $W/L = 3.95$. However, excessively large values of W/L

TABLE II: Influence of W/L ratio on $|S_{11}|$ bandwidth and realized gain.

W/L	BW (%)	G_R (ini) (dBi)	G_R (max) (dBi)	G_R (end) (dBi)
3.80	12.81	7.20	9.56	9.51
3.85	13.74	6.93	9.62	9.56
3.90	14.65	6.86	9.62	9.54
3.95	15.04	6.88	9.69	9.61

Frequency range (GHz): 3.80 (3.36–3.82), 3.85 (3.32–3.81), 3.90 (3.29–3.81), 3.95 (3.26–3.79).

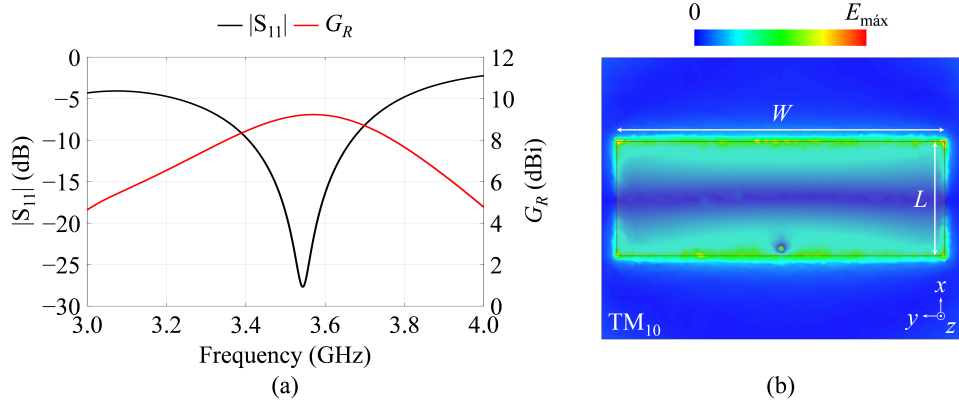


Fig. 2: Simulated results of Model 1. (a) Reflection coefficient and realized gain. (b) Electric field distribution (E_z) at $f_r \approx 3.58$ GHz.

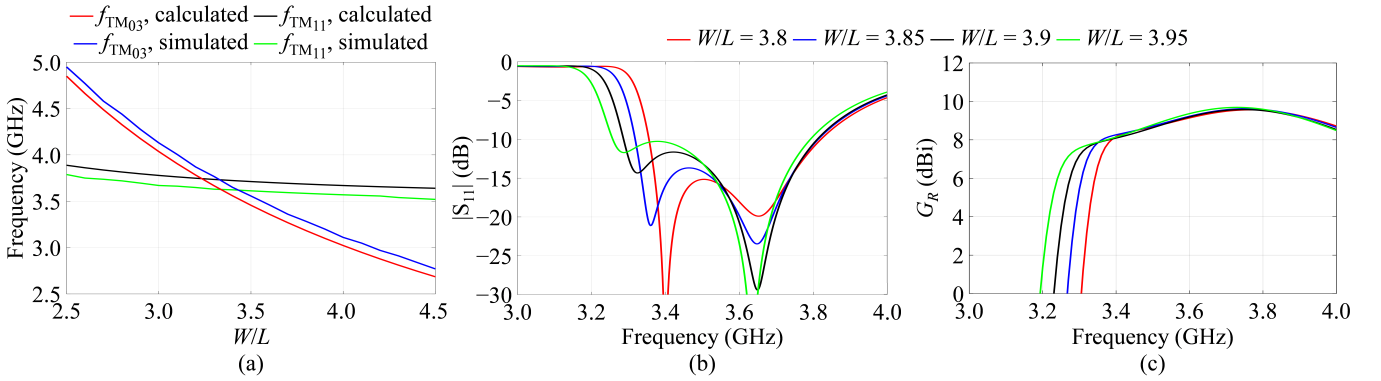


Fig. 3: Parametric analysis of Model 2 for different values of W/L . (a) Resonant frequencies of the TM_{03} -like and TM_{11} -like modes. (b) Reflection coefficient. (c) Realized gain.

also shift the operating band toward lower frequencies, while the increased separation progressively weakens the modal coupling. As a result, the impedance response tends toward a split-band behavior, with the TM_{03} -like resonance becoming mismatched.

The realized gain results shown in Fig. 3(c) indicate that the radiation performance remains nearly unchanged for all analyzed cases. The maximum realized gain stays close to 9.6 dBi, while the gain variation over the operating band remains small, demonstrating that the bandwidth enhancement obtained through modal coupling does not significantly affect the broadside directivity.

Based on these results, the ratio $W/L = 3.9$ was selected as the best tradeoff between bandwidth, gain stability, and operating frequency range. This configuration ensures full coverage of the allocated 3.3 to 3.8 GHz 5G band while preserving stable broadside radiation and proper modal coupling between the TM_{11} -like and TM_{03} -like resonances.

The modal behavior of the proposed antenna is further confirmed by the E_z field distributions shown in Fig. 4. At $f_r \approx 3.65$ GHz, the excited resonance corresponds to a TM_{11} -like mode. However, as shown in Fig. 4(a), the field distribution resembles the conventional TM_{10} mode, exhibiting a half-cycle variation along L and weak variation along

W . This behavior occurs because the shorting vias modify the cavity boundary conditions, replacing part of the open radiating edges with approximate electric walls. Consequently, the transverse field variation associated with the conventional TM_{11} mode is suppressed, making the resulting higher-order resonance physically similar to the TM_{10} mode, but distributed over a larger effective electrical area.

At $f_r \approx 3.32$ GHz, Fig. 4(b) shows three field variations along the dimension W and nearly uniform behavior along L , characterizing a TM_{03} -like mode. In this case, the shorting vias modify the cavity boundary conditions by replacing the corresponding radiating edges with approximate electric walls, suppressing the associated radiation mechanism. As a result, the excited higher-order mode becomes weakly radiating and mainly contributes to the additional resonance responsible for the bandwidth enhancement through modal coupling.

III. RESULTS AND DISCUSSIONS

To experimentally validate the proposed antenna, a prototype was manufactured and characterized. The structure was fabricated using a PCB-Proto 1S milling machine, followed by chemical etching to remove the remaining copper regions. Photographs of the fabricated prototype are presented in Fig. 5.

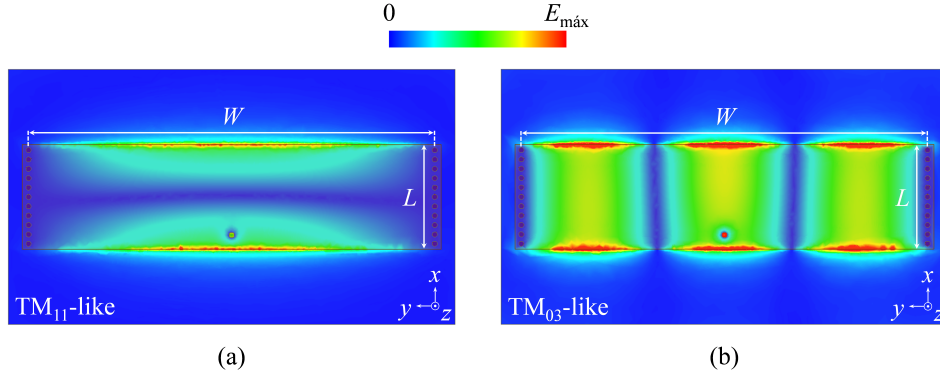


Fig. 4: Electric field distribution (E_z) of Model 2. (a) TM_{11} -like mode at $f_r \approx 3.65$ GHz. (b) TM_{03} -like mode at $f_r \approx 3.32$ GHz.

A. S-parameters and radiation performance

Figure 6 compares the simulated and measured reflection coefficients of the proposed antenna. The reflection coefficient was measured using a Tektronix TTR506A vector network analyzer. The measured results show good agreement with the simulations, confirming the validity of the adopted design approach. Experimentally, the antenna operates from 3.27 to 3.84 GHz for $|S_{11}| \leq -10$ dB, corresponding to a fractional bandwidth of approximately 16.0%. The small differences between the curves are mainly associated with fabrication tolerances and uncertainties in the dielectric substrate parameters. Nevertheless, the measured response preserves the dual-resonance characteristic, ensuring full coverage of the allocated 3.3 to 3.8 GHz 5G band.

Due to limitations in the available measurement setup, the radiation characteristics of the proposed antenna were evaluated only through full-wave simulations. The realized gain in the broadside direction ($\theta = 0^\circ$, $\phi = 0^\circ$), also shown in Fig. 6, ranges from 7.2 (at 3.3 GHz) to 9.6 dBi within the operating band, reaching a maximum at $f_r \approx 3.74$ GHz. These results indicate that the adopted multimode strategy provides bandwidth enhancement without significant degradation of gain performance.

The simulated radiation patterns at 3.3 GHz, 3.55 GHz, and 3.8 GHz are presented in Figs. 6(b)–(d). The results show stable broadside radiation throughout the operating band, with low sidelobe levels and good pattern stability. In the yz -plane, the copolarized field remains nearly unchanged over the analyzed frequencies, whereas in the xz -plane a slight asymmetry and main-lobe tilt are observed at lower frequen-

cies due to the reduced dominance of the TM_{11} -like mode near the lower resonance. In addition, the cross-polarization levels remain significantly lower than the copolarized radiation in both principal planes, confirming a good polarization purity across the entire operating band.

B. Comparative study

Table III compares the proposed antenna with recent sub-6 GHz 5G antennas reported in the literature, considering operating bandwidth, realized gain, and structural complexity. Most reported designs focus on compact MIMO terminal implementations, prioritizing multielement integration, isolation, and spectral coverage [13], [14], [15]. Consequently, these antennas typically exhibit low realized gain per element and require more complex multielement configurations. On the other hand, the antenna in [16] achieves very wide bandwidth and stable radiation characteristics through the combination of multiple resonant modes, but at the expense of a more complex multilayer structure employing folded walls and additional resonant elements.

Differently from these approaches, the proposed antenna achieves full coverage of the allocated 3.3 to 3.8 GHz 5G band using a simple single-layer microstrip configuration based on the controlled coupling between TM_{11} -like and TM_{03} -like modes. In addition to the enhanced impedance bandwidth, the antenna provides stable broadside radiation and realized gain between 7.2 and 9.6 dBi across the operating band, significantly higher than the gains reported for the compared terminal-oriented designs. Therefore, the proposed structure

TABLE III: Comparison of the proposed antenna with recent works for 5G applications around 3.5 GHz.

Ref.	Freq. Range (GHz)	BW (%)	Gain (dBi)	Complexity
[13]	3.27–5.92	57.7	0.0–2.0	High
[14]	3.3–3.6/4.4–5.0	8.7/12.8	0.0–1.0	High
[15]	3.4–3.7/4.8–5.0	8.5/4.1	0.5–0.7	Medium
[16]	2.84–5.36	61.5	4.4–6.2	High
This work*	3.29–3.81	14.6	7.2–9.6	Low

*Freq. Range, BW, and Gain refer to the simulated values of the antenna.

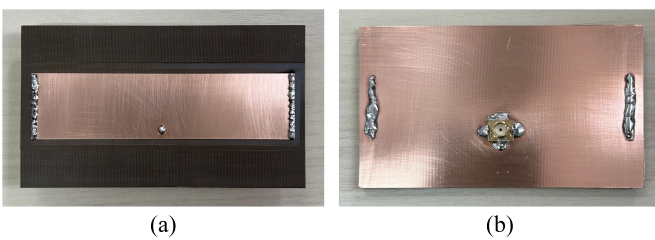


Fig. 5: Fabricated prototype of the proposed antenna. (a) Top view. (b) Bottom view.

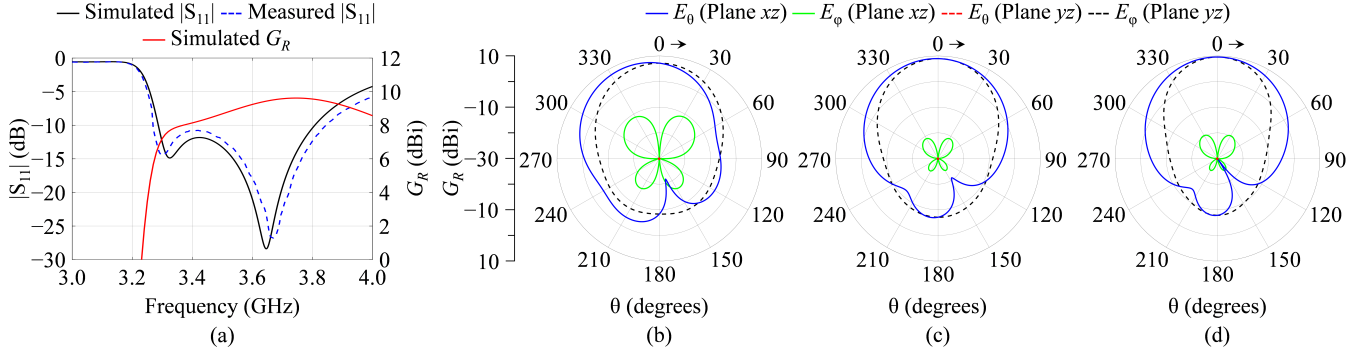


Fig. 6: Performance of the proposed antenna. (a) Reflection coefficient and realized gain versus frequency. (b) Radiation patterns at 3.3 GHz. (c) Radiation patterns at 3.55 GHz. (d) Radiation patterns at 3.8 GHz.

provides an attractive tradeoff among bandwidth, gain, radiation stability, and structural simplicity for sub-6 GHz 5G applications.

IV. CONCLUSIONS

This paper presented a wideband and high-gain multimode MPA for 3.5 GHz 5G applications. The proposed design uses shorting vias to modify the cavity boundary conditions and control the coupling between TM_{11} -like and TM_{03} -like modes, producing a dual-resonance response that extends the impedance bandwidth while preserving broadside radiation. The antenna fully covers the allocated 3.3 to 3.8 GHz band, with a simulated bandwidth of 14.6% and a measured bandwidth of 16.0%, showing good agreement between simulation and experiment. In addition, the structure achieves realized gain from 7.2 to 9.6 dBi, stable radiation patterns, low cross-polarization levels, and a simple single-layer implementation. These results demonstrate that the proposed multimode strategy provides an effective tradeoff among bandwidth, gain, radiation stability, and structural simplicity, making the antenna a competitive solution for sub-6 GHz 5G systems.

ACKNOWLEDGMENTS

The authors would like to thank FAPEMIG (scholarship no. 11326 to F. S. Borges) for the financial support.

REFERENCES

- [1] M. Mehri Pashaki, M. H. Koohi Ghamsari, A. Mallahzadeh, G. Gradoni, and M. Khalily, "A Corrugated All-Metal Vivaldi Antenna for 5G Phased Array Applications," *IEICE Trans. Commun.*, vol. E108-B, no. 8, pp. 870–875, 2025.
- [2] S.-H. Cheng, S.-C. Chen, and W.-Y. Huang, "Low-Profile MIMO Trapezoidal Patch Antenna for 5G Wideband Mobile Antenna Application," *IEEE Antennas Wireless Propag. Lett.*, vol. 24, no. 3, pp. 696–700, 2025.
- [3] Agência Nacional de Telecomunicações (ANATEL), "Act No. 915, Feb. 01, 2024: Technical and operational requirements for the use of radio frequency bands associated with the private limited service," <https://informacoes.anatel.gov.br/legislacao/atos-de-requisitos-tecnicos-de-gestao-do-espectro/2024/1920-ato-915>, Brasília, Brazil, 2024, accessed: May. 07, 2026.
- [4] —, "Act No. 16539, Nov. 17, 2023: Technical and operational requirements for the use of radio frequency bands associated with the collective interest services," <https://informacoes.anatel.gov.br/legislacao/atos-de-requisitos-tecnicos-de-gestao-do-espectro/2023/1904-ato-16539>, Brasília, Brazil, 2023, accessed: May. 07, 2026.
- [5] J. Cheng, H. Qiu, X. Shen, D. Zeng, M. Li, Z. Wang, and Z. Yi, "A Compact Low-Profile Vehicular 5G MIMO Antenna System," *IEEE Antennas Wireless Propag. Lett.*, vol. 24, no. 8, pp. 2422–2426, 2025.
- [6] P. Bhartia, I. Bahl, R. Garg, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA, USA: Artech House, 2001.
- [7] J. Wen, D. Xie, and L. Zhu, "Bandwidth-Enhanced High-Gain Microstrip Patch Antenna Under TM_{30} and TM_{50} Dual-Mode Resonances," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 1976–1980, 2019.
- [8] Z. Wang, J. Liu, and Y. Long, "A Simple Wide-Bandwidth and High-Gain Microstrip Patch Antenna With Both Sides Shorted," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 6, pp. 1144–1148, 2019.
- [9] Y. Cao, Y. Cai, W. Cao, B. Xi, Z. Qian, T. Wu, and L. Zhu, "Broadband and High-Gain Microstrip Patch Antenna Loaded With Parasitic Mushroom-Type Structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 7, pp. 1405–1409, 2019.
- [10] D. Jackson and N. Alexopoulos, "Simple approximate formulas for input resistance, bandwidth, and efficiency of a resonant rectangular patch," *IEEE Trans. Antennas Propag.*, vol. 39, no. 3, pp. 407–410, 1991.
- [11] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ: Wiley, 2016.
- [12] R. W. Dearnley and A. R. F. Barel, "A comparison of models to determine the resonant frequencies of a rectangular microstrip antenna," *IEEE Trans. Antennas Propag.*, vol. 37, no. 1, pp. 114–118, Jan. 1989.
- [13] H.-D. Chen, Y.-C. Tsai, C.-Y.-D. Sim, and C. Kuo, "Broadband Eight-Antenna Array Design for Sub-6 GHz 5G NR Bands Metal-Frame Smartphone Applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 7, pp. 1078–1082, 2020.
- [14] W. Hu, Q. Li, H. Wu, Z. Chen, L. Wen, W. Jiang, and S. Gao, "Dual-Band Antenna Pair With High Isolation Using Multiple Orthogonal Modes for 5G Smartphones," *IEEE Trans. Antennas Propag.*, vol. 71, no. 2, pp. 1949–1954, 2023.
- [15] L. Chang and H. Wang, "Dual-Band Four-Antenna Module Covering N78/N79 Based on PIFA for 5G Terminals," *IEEE Antennas Wireless Propag. Lett.*, vol. 21, no. 1, pp. 168–172, 2022.
- [16] W. An, Y. Li, H. Fu, J. Ma, W. Chen, and B. Feng, "Low-Profile and Wideband Microstrip Antenna With Stable Gain for 5G Wireless Applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 4, pp. 621–624, 2018.