

Compact Circularly Polarized Patch Antenna for NTN Applications

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Abstract—Non-Terrestrial Networks (NTNs), standardized by 3GPP, integrate satellite constellations into 5G networks, requiring antennas optimized for direct satellite-to-device communication with maximum efficiency in the zenith direction. This article presents the design of a circular patch antenna with circular polarization (CP) for the 3GPP n255 band (uplink: 1626.5 to 1660.5 MHz), with a center frequency of 1650 MHz. Circular polarization is achieved through quadrature orthogonal dual feeding, using two microstrip lines coupled to the patch, with a phase shift of 90° . Simulations performed in ANSYS - HFSS, together with measurements of a first prototype, demonstrate a reflection coefficient $|S_{11}| < -10$ dB, an axial ratio (AR) of less than 1 dB in the zenith direction, a gain of 2.10 dBic, and a radiation efficiency of 75% at 1.65 GHz. With compact dimensions (80×80 mm) and the use of an FR-4 substrate, the proposed antenna is feasible for large-scale production in IoT terminals intended for NTN applications.

Keywords—Patch Antenna, Circular Polarization, Non-Terrestrial Networks, 3GPP NTN, Band n255.

I. INTRODUCTION

Non-Terrestrial Networks (NTN) have emerged as a strategic solution to extend wireless communication coverage beyond the limitations of terrestrial infrastructure. By integrating platforms such as low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary (GEO) satellites with fifth-generation (5G) and future communication systems, NTN enable global connectivity, reaching remote regions, rural areas, oceans, and disaster-affected zones [1].

In this scenario, NTN play a key role in supporting critical applications, including environmental monitoring, maritime and aeronautical communications, as well as emergency services [2]. In particular, Internet of Things (IoT) applications require reliable, long-range, and energy-efficient communication solutions, making NTN especially attractive.

From an operational perspective, NTN rely on direct communication between user terminals and satellites, which act as relay nodes linking the space segment to ground stations connected to the core network. While this approach significantly expands the coverage of conventional mobile networks, it also introduces technical challenges, such as high propagation losses, satellite mobility, channel variability, and ionospheric effects [3]. Figure 1 illustrates a simplified NTN architecture.

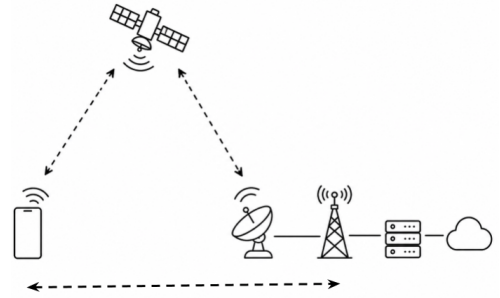


Fig. 1: Simplified architecture of an NTN system.

Among the factors that directly impact system performance, antennas play a crucial role, as they establish the communication link with the satellite. For this reason, requirements such as low profile, compact size, lightweight structure, and ease of integration are particularly important, especially for IoT devices and portable terminals. Additionally, circular polarization is widely adopted in satellite communications due to its robustness against Faraday rotation and multipath fading effects [4].

Despite these advantages, the design of antennas capable of simultaneously meeting all these requirements remains challenging, particularly in the L-band, where bandwidth limitations and physical size constraints are significant. Therefore, the development of compact and efficient antenna solutions with robust electromagnetic performance is essential to enable practical NTN applications. In this context, this article presents the design of a circular patch antenna with circular polarization (CP) for the 3GPP n255 band (uplink: 1626.5 to 1660.5 MHz).

The remainder of this article is organized as follows: Section II presents the state of the art; Section III describes the antenna design, including its geometry, parameters, and operating principles. Section IV discusses the obtained results, including the reflection coefficient, axial ratio, and radiation patterns. Finally, Section V concludes the article and outlines future work.

II. LITERATURE REVIEW

A variety of L-band antenna designs have been reported in the literature, primarily targeting GNSS applications and, more recently, NTN systems. Microstrip patch antennas are widely adopted due to their low-profile structure and compatibility with planar fabrication techniques [5], [6]. Most designs rely on square or rectangular patches with geometric modifications to achieve circular polarization. Common approaches include corner truncation [7], [8], which offers a simple way to excite

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orthogonal degenerate modes, and quadrature feeding using hybrid networks [9], which provides improved polarization purity at the expense of increased feeding complexity.

However, conventional patch antennas inherently suffer from narrow bandwidth, particularly regarding impedance matching and axial ratio performance [10]. To address this limitation, several techniques have been explored. Methods such as asymmetric slotting and the use of grounding vias [11], as well as patch texturing [12], aim to enhance both bandwidth and polarization characteristics. Additionally, antenna arrays can be employed to increase gain, although this comes with higher complexity and larger physical dimensions [13].

More recently, multilayer configurations have gained attention as an effective solution for bandwidth enhancement. In [14], a four-layer circularly polarized antenna achieves an impedance bandwidth from 3.35 to 6.45 GHz, AR below 3 dB, and a gain of 7.5 dBi. In [15], a multilayer patch antenna incorporating shorting vias, a coupled ring, and a parasitic patch reaches an impedance bandwidth of 28% at 1.8 GHz and 6.4% at 2.4 GHz, with a maximum gain of 4.46 dBi. Furthermore, a multilayer circular patch fabricated using additive manufacturing demonstrates a bandwidth improvement of approximately 10% [16]. These results highlight the potential of multilayer structures to overcome the intrinsic limitations of conventional patch antennas.

Despite these advances, most studies focus on GNSS applications and do not explicitly address NTN-specific requirements, such as operation in the n255 band, integration into compact IoT devices, and optimized radiation toward the zenith for satellite links.

To address these challenges, this work proposes a circularly polarized microstrip patch antenna operating in the L-band n255 (1.525–1.6605 GHz). The design is based on a circular patch with dual-feed excitation, using two orthogonal ports with a 90° phase difference to generate right-hand circular polarization (RHCP), ensuring high polarization purity without the need for complex hybrid networks. In addition, a multilayer configuration is adopted to enhance bandwidth through the excitation of multiple resonances. The antenna is optimized to provide hemispherical radiation with maximum gain at the zenith, AR below 3 dB, and stable impedance matching across uplink and downlink bands, while maintaining a compact and low-profile structure suitable for NTN IoT applications.

III. ANTENNA DESIGN

A. Geometry and Parameters

Initially, a circular patch antenna model was developed based on classical microstrip antenna formulations and reference works focused on circular structures [17], [18]. The choice of a circular geometry is justified by its ability to support orthogonal degenerate modes, which facilitates the generation of circular polarization. The antenna dimensions were defined to operate around 1.65 GHz by adjusting the patch radius and substrate properties.

The antenna was designed using an FR-4 substrate, with a relative permittivity of 4.40 and a thickness of 1.60 mm. This material is widely used due to its low cost and ease of

fabrication [19]. However, due to possible variations in the permittivity of FR-4, adjustments were made to the model based on the simulated response to align the antenna performance with the desired operating frequency.

The analysis and optimization of the geometric parameters were carried out through simulations using the Ansys HFSS software [20]. The antenna was subsequently fabricated using an LPKF-S64 prototyping machine. Figure 2 presents the antenna geometry and its main parameters, while Figure 3 shows the fabricated prototype.

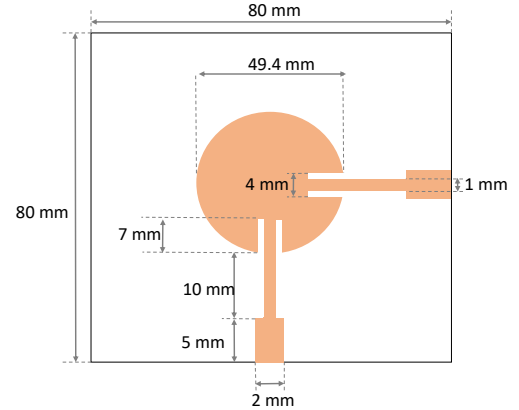


Fig. 2: Parameters of the proposed antenna.

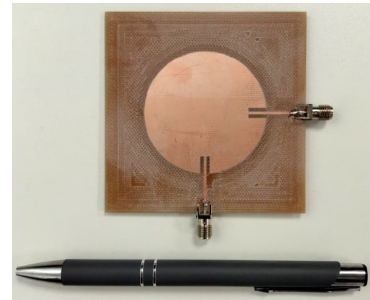


Fig. 3: Fabricated antenna.

B. Circular Polarization Generation

Circular polarization is achieved through the simultaneous excitation of two orthogonal degenerate modes in the circular patch. For this purpose, the antenna is fed by two orthogonally positioned ports excited with a 90° phase difference, a widely used technique for generating quadrature modes [21]. In the numerical model, equal magnitudes were assigned to both ports, with a 90° phase difference between them. The antenna dimensions were iteratively adjusted to achieve good matching to 50Ω . These factors are essential for obtaining a low AR, which is a fundamental parameter for assessing the quality of circular polarization.

C. Bandwidth Enhancement Using a Hybrid Multilayer Structure

The analysis presented in the previous section showed that the proposed single-layer antenna exhibits the narrow impedance bandwidth typically associated with conventional

microstrip antennas. Therefore, in order to enhance the bandwidth while preserving a compact planar geometry and maintaining a low fabrication cost, a hybrid multilayer configuration based on electromagnetic coupling between two radiating elements was proposed.

The proposed structure combines two dielectric substrates with distinct electromagnetic characteristics. The lower layer consists of an FR4 laminate with dimensions of 80×80 mm and a thickness of 3.2 mm, which supports the driven radiating element, the ground plane, and the entire feeding network. The upper layer consists of a Rogers laminate with dimensions of 64×64 mm and a thickness of 3.2 mm, on which a parasitic radiating element is printed.

The mechanical assembly of the antenna will be accomplished using a PLA spacer fabricated through additive manufacturing (3D printing). This spacer will maintain a 5 mm air gap between the FR4 and Rogers substrates, ensuring proper alignment of the layers and the mechanical stability of the structure without establishing any electrical contact between them. Consequently, the coupling between the driven patch and the parasitic patch will occur exclusively through the electromagnetic field in the air-gap region. A similar mechanical implementation was reported in [8], where a PLA spacer was employed to maintain the separation between the substrates while providing structural stability to the antenna.

The bandwidth enhancement mechanism is based on the electromagnetic coupling between the driven patch, located on the lower layer, and the parasitic patch, located on the upper layer. Energy is transferred through the air-gap region, exciting a second resonant mode close to the operating frequency of the primary radiating element. The overlap of these resonant modes results in a significant increase in the impedance bandwidth without increasing the planar dimensions of the antenna, thus preserving a compact structure suitable for satellite communication applications and other microwave systems [22].

Figure 4 illustrates the proposed multilayer configuration, highlighting the relative arrangement of the FR4 and Rogers substrates, the 5 mm air gap, and the electromagnetic coupling mechanism adopted in this work.

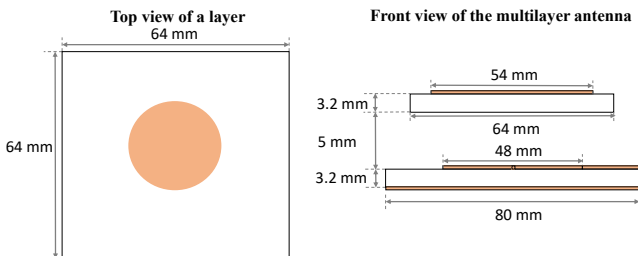


Fig. 4: Schematic representation of the multilayer model.

IV. RESULTS AND DISCUSSIONS

Before evaluating the proposed multilayer configuration, the single-layer antenna was fabricated and experimentally characterized to validate the numerical model, the feeding network, and the circular polarization generation technique.

This stage provides the experimental baseline for the development of the multilayer structure. Since the performance of the proposed configuration depends on additional design parameters, particularly the air-gap thickness between the two substrates, further optimization studies are still required to define its final geometry. Therefore, at this stage of the work, only the reference antenna was fabricated, while the multilayer configuration was evaluated through full-wave electromagnetic simulations. The fabrication and experimental characterization of the optimized multilayer prototype will be carried out after the completion of the optimization process.

A. Reflection Coefficient

It is known that the relative permittivity (ϵ_r) of FR-4 can typically vary between 3.8 and 4.8. Therefore, a parametric analysis was performed by varying the ϵ_r of the FR-4 substrate in order to evaluate the impact of the permittivity on the proposed antenna. The simulated results are shown in Figure 5.

After the measurements were carried out, it was found that the ϵ_r of the fabricated board should be approximately 4.3. Figure 6 shows the simulated and measured S_{11} results for the single-layer model. The simulated S_{11} result for the multilayer model is also presented. The measured and simulated results of the single-layer antenna exhibit good agreement. Despite the frequency deviation, the model proved to be functional, since the reflection coefficient shows good impedance matching at the frequency of interest. This model exhibited a bandwidth of 30 MHz below -10 dB, corresponding to 1.78% with respect to the central frequency of 1.68 GHz. Figure 6 also presents the simulated and measured S_{21} results for the single-layer antenna, as well as the simulated S_{21} result for the multilayer model. In all cases, the S_{21} values indicate good isolation between the ports, as desired.

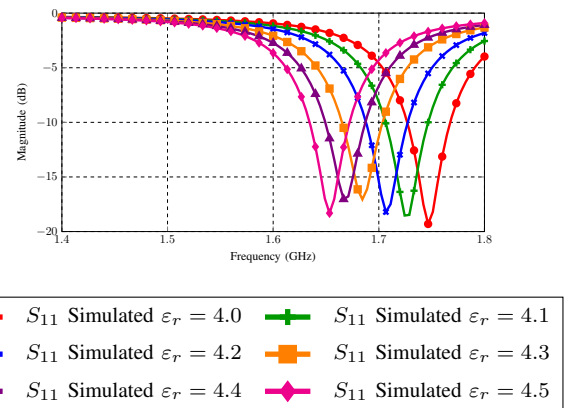
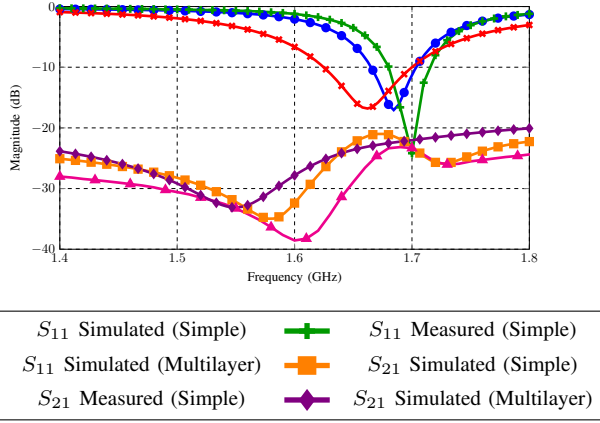


Fig. 5: S -parameters as a function of frequency for different dielectric constants (ϵ_r).

The simulated S_{11} of the improved multilayer model demonstrates a bandwidth of approximately 77.8 MHz. This significant improvement, greater than a twofold increase in bandwidth, is a direct consequence of the electromagnetic coupling technique between the resonant layers. The multilayer model maintains the required impedance matching at the central frequency, with $S_{11} < -15$ dB, demonstrating that the


 Fig. 6: S -parameters as a function of frequency.

bandwidth enhancement did not compromise the quality of the 50Ω matching.

B. Axial Ratio - AR

Figure 7 presents the simulated AR results in the zenith direction ($\theta = 0^\circ$) for the simple model. A sweep was performed considering the phase difference between the antenna ports. For a phase difference of 90° , the best AR result was obtained, corresponding to approximately 0.5 dB at the resonant frequency. It should be highlighted that, considering the 3 dB tolerance, the phase difference between the antenna ports is acceptable within the range from 70° to 110° .

Additionally, Figure 8 shows the simulated axial ratio results in the $\theta = 0^\circ$ direction for the multilayer model. In this case, it can be observed that the best AR result occurs for a phase difference of 90° . Furthermore, considering the 3 dB tolerance, an acceptable phase difference between the antenna ports is greater than 70° and lower than 110° . It is observed that both models achieve an AR below 3 dB, which is consistent with the literature for circular polarization applications.

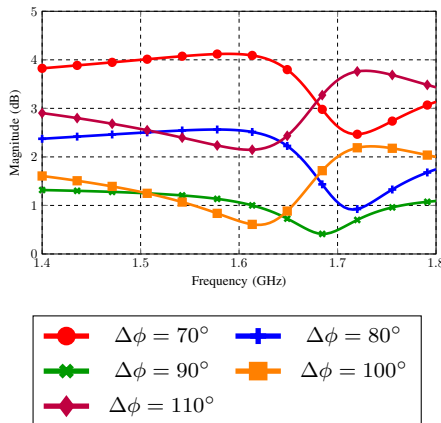


Fig. 7: Axial ratio as a function of the phase difference between the antenna ports, considering the simple model.

C. Radiation Pattern

A Figure 9 presents the simulated radiation patterns in the $\phi = 0^\circ$ plane for the left-hand circular polarization (LHCP)

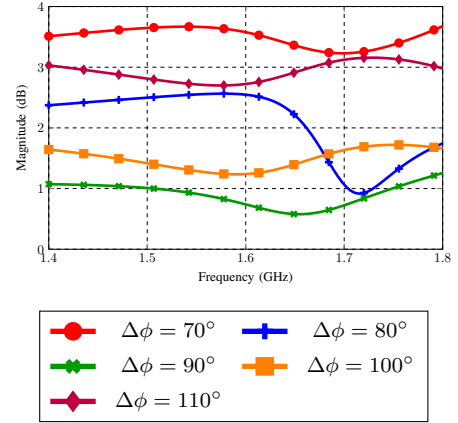
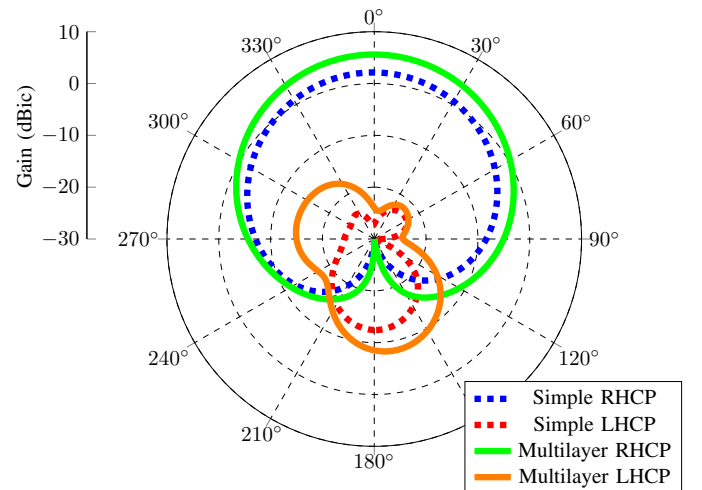


Fig. 8: Axial ratio as a function of the phase difference between the antenna ports, considering the multilayer model.

and RHCP components, comparing the two developed models when the phase difference between the antenna ports is 90° . For the simple model, represented by the dashed curves, a gain of 2.10 dBic in the zenith direction is highlighted. The predominance of the RHCP component in the zenith direction is observed, with a significantly lower LHCP polarization level. The symmetry of the radiation pattern is consistent with the circular geometry maintained in the configuration. It should be noted that, if the phase difference is -90° , the LHCP component would become significantly dominant, while the RHCP component would exhibit lower levels.

Figure 9 also presents the RHCP and LHCP results for the multilayer model. The gain in the zenith direction is 5.50 dBic, representing a significant increase compared to the single-layer model, with XPD and front-to-back ratio values of -25 dB and -14 dB, respectively. Both models exhibit a radiation efficiency of approximately 75%. Figure 10 shows the RHCP and LHCP results for both models at $\theta = 90^\circ$. For both models, the RHCP results remain higher than the LHCP results. However, considering the azimuth results ($\theta = 90^\circ$), the difference between RHCP and LHCP is smaller when compared to the elevation results ($\phi = 0^\circ$).


 Fig. 9: Radiation pattern in the $\phi = 0^\circ$ plane.

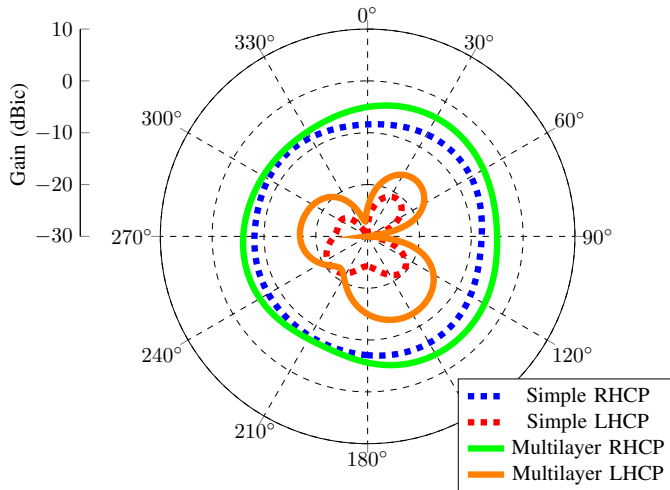


Fig. 10: Radiation pattern in the $\theta = 90^\circ$ plane.

V. CONCLUSIONS AND FUTURE WORK

This work presented the design of a compact circular patch antenna with circular polarization for non-terrestrial network (NTN) applications in the L-band n255. The baseline antenna employs orthogonal dual-feed with a 90° phase shift to generate RHCP with high polarization purity ($AR < 0.6$ dB) and a gain of 5.50 dBic in the zenith direction. To overcome the intrinsic narrowband limitation of conventional patch antennas, a multilayer structure was proposed, expanding the impedance bandwidth from approximately 30 MHz to 77.8 MHz, representing an increase of 2.6 times. The simulated results demonstrate that this improvement was achieved without significantly compromising the radiation characteristics, polarization purity, or planar dimensions of the antenna. The use of FR-4 and Rogers substrates, combined with the compact dimensions (80×80 mm), makes the antenna viable for integration into low-cost IoT terminals intended for direct satellite communication. As future work, the multilayer prototype will be fabricated and experimentally characterized, and additional techniques for optimizing the AR bandwidth will be investigated to simultaneously meet the uplink and downlink requirements of the n255 band.

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