6G-INTEGRATION-IV-E6: WIRELESS LINK

6G-INTEGRATION-I-E7

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Executive Summary

This document provides a detailed description of the implemented solution for the 6G-Integration project through the development of super wideband (SWB) antenna technologies, focusing on the Volcano Smoke Antenna (VSA) geometry and its application in both monopole configurations (3D and 2D) and 4-port MIMO systems. The research, led by UC3M and its collaborators, addresses the challenges of extreme bandwidth, high gain, compactness, and electromagnetic isolation in portable and reconfigurable antennas.

The proposal begins with the design of a volumetric three-dimensional antenna (3D-VSA), which incorporates an optimized curved ground plane through parametric studies and analytical modeling. This model achieves outstanding performance with a bandwidth ratio of 32:1 (1.5–48.2 GHz) and a maximum gain of 5.75 dBi. Simultaneously, a planar 2D version was developed on an FR4 substrate, achieving comparable performance (2.38–49.8 GHz) and a maximum gain of 6.7 dBi, with key benefits in low-cost manufacturing and compatibility with PCB technology for large-scale integration.

Both antennas were designed to operate across frequency ranges covering mid-band 5G to millimeter-wave B5G bands, with cross-polarization levels below –10 dB and good impedance matching (VSWR ≤ 2). These antennas are positioned as foundational platforms for sensing solutions, IoT connectivity, and compact mobile devices.

As a natural extension, a 2×2 port MIMO system was designed and validated using the optimized VSA geometry. This configuration, implemented on an FR4 board, uses a VSA unit cell with an aperture angle of φ = 65° and dimensions of 65×65 mm, achieving S11 levels below –10 dB and S12 isolation better than –13.32 dB across the 2.73 to 43.38 GHz range. Simulations and measurements confirmed the presence of null lobes characteristic of well-decoupled MIMO structures.

The interconnection between both development lines—the progressive evolution of VSA monopoles in 3D/2D versions and their direct application in MIMO systems—demonstrates the versatility of this geometry to simultaneously meet requirements for gain, bandwidth, portability, and multichannel configuration.

Both developments were validated through CST simulations and experimental testing in anechoic chambers, highlighting the fidelity between models and physical prototypes (3D-printed, aluminum-machined, or PCB-fabricated). When benchmarked against state-of-the-art UWB and SWB antennas, the proposed VSA set was shown to outperform or match them in gain and bandwidth, with smaller electrical size and broader practical applicability.

These solutions establish VSA-based antennas as strategic candidates for future 5G/B5G infrastructure deployments, compact base stations, sensor networks, satellite links, and high-performance reconfigurable nodes.

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Resumen ejecutivo

Este documento proporciona una descripción detallada de la solución implementada para el proyecto 6G-Integration, mediante las soluciones desarrolladas para la evolución de antenas de súper banda ancha (SWB) en el marco de las tecnologías 5G y B5G, centrándose en la geometría Volcano Smoke Antenna (VSA) y su aplicación tanto en configuraciones monopolo (3D y 2D) como en sistemas MIMO de 4 puertos. La investigación, impulsada por UC3M y sus colaboradores, aborda los desafíos de ancho de banda extremo, alta ganancia, compacidad y aislamiento electromagnético en antenas portátiles y reconfigurables.

La propuesta parte del diseño volumétrico tridimensional (3D-VSA), que incorpora un plano de tierra curvo optimizado mediante estudios paramétricos y modelado analítico. Este modelo logra un rendimiento sobresaliente con una relación de ancho de banda de 32:1 (1.5–48.2 GHz) y una ganancia máxima de 5.75 dBi. Paralelamente, se desarrolla una versión planar 2D sobre sustrato FR4, logrando un desempeño comparable (2.38–49.8 GHz) y una ganancia máxima de 6.7 dBi, con beneficios clave en términos de fabricación económica y compatibilidad con tecnología PCB para integración masiva.

Ambas antenas fueron diseñadas para operar en rangos que cubren desde las bandas medias de 5G hasta frecuencias milimétricas propias de B5G, presentando niveles de polarización cruzada inferiores a –10 dB y buena adaptación de impedancia (VSWR ≤ 2). Estas antenas se consolidan como plataformas base para soluciones de sensado, conectividad IoT y dispositivos móviles compactos.

Como extensión natural, se diseñó y validó un sistema MIMO de 2×2 puertos utilizando la geometría VSA optimizada. Esta configuración, integrada sobre un plano FR4, emplea una celda unitaria VSA con ángulo de apertura φ = 65° y dimensiones de 65×65 mm, alcanzando niveles de S11 por debajo de –10 dB y de aislamiento S12 menores a –13.32 dB en todo el rango de 2.73 a 43.38 GHz. Las simulaciones y mediciones confirmaron la aparición de lóbulos nulos característicos de estructuras MIMO bien desacopladas.

La interrelación entre ambas líneas de desarrollo —la evolución progresiva de VSA monopolo en versiones 3D/2D y su aplicación directa en sistemas MIMO— demuestra la versatilidad de esta geometría para satisfacer simultáneamente requisitos de ganancia, ancho de banda, portabilidad y configuración multicanal.

Ambos desarrollos se validaron mediante simulaciones en CST y pruebas experimentales en cámara anecoica, destacando la fidelidad entre modelos y prototipos físicos (impresos en 3D, mecanizados en aluminio o fabricados en PCB). Se compararon frente a referencias del estado del arte en antenas UWB y SWB, confirmando que el conjunto VSA propuesto supera o iguala el rendimiento en ganancia y ancho de banda, con menor tamaño eléctrico y mayor aplicabilidad práctica.

Estas soluciones consolidan a las antenas VSA como candidatas estratégicas para futuras implementaciones de infraestructura 5G/B5G, estaciones base compactas, redes de sensores, enlaces satelitales y nodos reconfigurables de alto desempeño.

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Glossary

Term	Definition
CAV (Confined Acoustic Vibrations)	Mechanical vibrations confined within nanoscale structures like virions, which resonate when excited by microwave fields.
MAS (Microwave Absorption Spectrum)	The frequency-dependent profile showing how a sample absorbs microwave energy due to resonant phenomena.
SPH Mode	A spheroidal vibration mode with angular momentum l=1l = 1, n=0n = 0, the only mode that couples effectively with electromagnetic fields in spherical particles.
Dipolar Coupling	The interaction between an external electric field and a charged particle system, inducing dipole-like mechanical oscillations.
Q-Factor	Quality factor of a resonant system indicating the sharpness and energy loss rate of resonance. High Q means low energy dissipation.
σabs (Absorption Cross-Section)	An effective area quantifying how much incident microwave power is absorbed by a single virion.
Nsup (Superficial Density)	Number of virions per square meter (vp/m^2) present on the surface of a sensor substrate.
Nvol (Volumetric Density)	Number of virions per cubic meter (vp/m^3) suspended in a fluid medium.
VNA (Vector Network Analyzer)	Instrument used to measure the scattering parameters (S11, S21, etc.) of RF and microwave systems.
S21 Parameter	A measure of forward transmission in a 2-port system. Changes in S21 indicate the presence of absorbing material (e.g., viruses).
Antenna-Based Sensor	Sensing system that uses horn antennas to transmit and receive microwave signals through a virus-laden sample.
Waveguide-Based Sensor	Sensing system using a guided microwave structure with an integrated fluidic channel for virus sample interaction.

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Term	Definition
Rayleigh Scattering	Scattering of electromagnetic waves by particles much smaller than the wavelength; usually negligible in microwave-range virus detection.
5G/6G Technologies	Fifth and sixth generation mobile communication standards. Offer high frequencies and dense connectivity for IoT and real-time biosensing.
Aptamer	Short DNA or RNA molecules used to specifically bind target molecules, like viruses, in biosensors.
Double Mass-Spring Model	A mechanical analog used to simulate the oscillatory behavior of a virus when subjected to microwave excitation.
VSWR (Voltage Standing Wave Ratio)	A metric used to quantify impedance matching in RF systems. A low VSWR (<2) indicates efficient power transmission.
Microwave Resonant Absorption	Process where microwave energy is converted into mechanical vibration energy within a target particle, leading to detectable losses in signal.
Functionalization	The chemical process of coating a substrate with molecules (e.g., aptamers) to ensure selective virus binding.

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1. Introduction

The rapid expansion of wireless communication systems, driven by the implementation of 5G technologies and the development of B5G platforms, has created a growing demand for compact, high-gain antennas capable of operating over extremely wide bandwidths. These antennas must not only provide efficient coverage in mid and millimeter-wave bands, but also allow integration into portable devices, IoT nodes, and high-density communication systems. In this context, the antenna known as the Volcano Smoke Antenna (VSA), originally proposed by Kraus in the 1940s [1], has re-emerged as a versatile geometric structure for ultra-wideband (UWB) and super-wideband (SWB) applications.

The geometry of the VSA has evolved in two main directions. First, a three-dimensional volumetric antenna (3D-VSA) with a curved ground plane was developed, optimized through analytical modeling and parametric studies that stabilized the input impedance and improved gain. This design achieved a bandwidth ratio of 32:1 (1.5–48.2 GHz) and a maximum measured gain of 5.75 dBi [46, p. 5]. Secondly, a planar version (2D-VSA) was designed using an FR4 substrate, offering comparable electromagnetic performance (2.38–49.8 GHz), with a gain of up to 6.7 dBi and key advantages in terms of low cost and compatibility with printed circuit boards [1, p. 7].

Complementing these developments, a 4-port MIMO architecture based on the same VSA geometry was proposed, featuring an optimized unit cell ($\phi = 65°$, dimensions 65 × 65 mm). This configuration achieved a reflection coefficient $S11 \leq -10$ dB and an isolation level S12 below –13.32 dB in the range of 2.73 to 43.38 GHz, meeting the demanding requirements of SWB MIMO systems [2, p. 2].

The experimental and numerical results obtained for both development lines (monopole and MIMO) demonstrate the feasibility and adaptability of the VSA geometry to simultaneously meet criteria of high performance, low profile, and integration flexibility. These characteristics position VSA antennas as strategic candidates for application in 5G/B5G base stations, distributed sensors, satellite links, and next-generation reconfigurable devices.

2. Volcano Smoke Antenna Design

2.1. 2D Planar VSA for PCB Integration

The three-dimensional design of the Volcano Smoke Antenna (3D-VSA) stems from the evolution of the classic coaxially fed monocone, to which a hemisphere is added at its tip and an optimized curved ground plane is incorporated. This geometry aims to maximize bandwidth and impedance matching across a wide frequency range.

The theoretical analysis is based on the input impedance model of a biconical antenna, using simplifications through TEM modes and Hankel functions. After analytical and numerical validation using CST, the optimal conditions were identified for the flare angle ($\theta = 37°$) and the vertex truncation ($\Delta h = 0.4$ mm), as shown in Figures 1 and 2.

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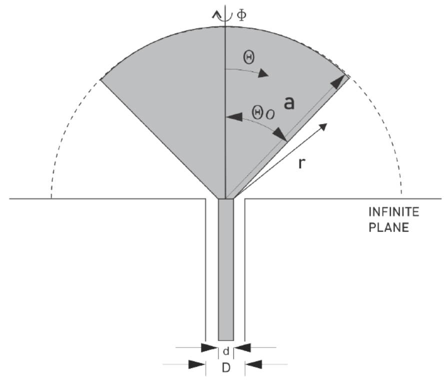

Figure 1: Cross-sectional view of the 3D-VSA design with curved ground plane

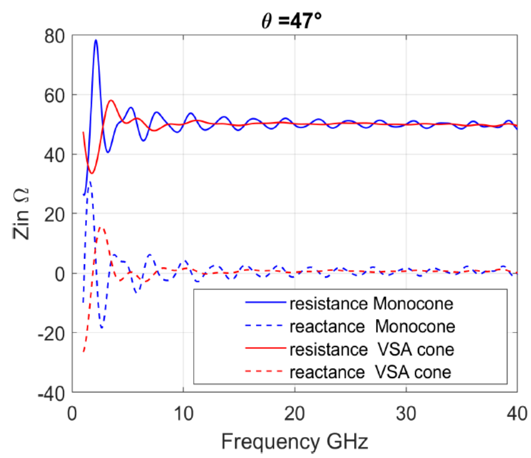

Figure 2: Simulated impedance comparison between classic monocone and VSA models

Table 1: Physical parameters of the 3D-VSA prototype

Parameter	Value
Monocone height (h_1)	52.5 mm
Radiating element radius (R)	19.85 mm
Δh	0.4 mm
Ground plane radius (w)	52.5 mm
Variable height (h_2–h_3)	3.5–7.5 mm
Measured VSWR	≤ 2 over 1.5–48.2 GHz
Maximum gain	5.75 dBi

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2.2 2D Planar VSA for PCB Integration

To reduce the system's volume without sacrificing electromagnetic performance, a planar version of the VSA was designed and fabricated on an FR4 substrate. The 2D-VSA is derived from a vertical cross-section of the 3D model, adapted to PCB technology using a microstrip configuration.

After four stages of parametric optimization (Fig. 3), improvements in the VSWR were achieved through adjustments in the ground plane position, taper line geometry, and the addition of semicircular elements.

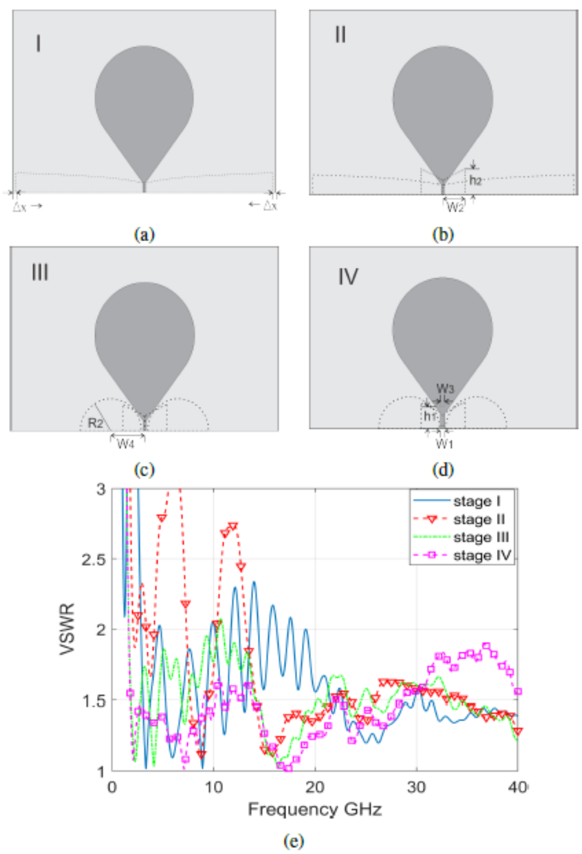

Figure 3: Optimization stages of the 2D-VSA design (I to IV)

Table 2: Optimized dimensions of the 2D-VSA prototype

Parameter	Value
Total height (H)	30.3 mm
h_1, h_2, h_3	5.45 / 9.75 / 8.27 mm
Widths W_1–W_4	1.76 / 8.65 / 1.54 / 10.72 mm
Substrate	FR4 (εr = 4.3)
BW (VSWR ≤ 2)	2.38–49.89 GHz

2.3 Unit Cell Optimization for MIMO Systems

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La geometría de la VSA también fue implementada en una arquitectura MIMO 2×2, mostrado en la figura 4, utilizando una celda unitaria optimizada sobre PCB (ϕ = 65°, dimensiones 65×65 mm). El diseño fue validado mediante simulaciones y mediciones, logrando un S11 ≤ –10 dB y un aislamiento S12 < –13.32 dB en todo el rango de 2.73 a 43.38 GHz

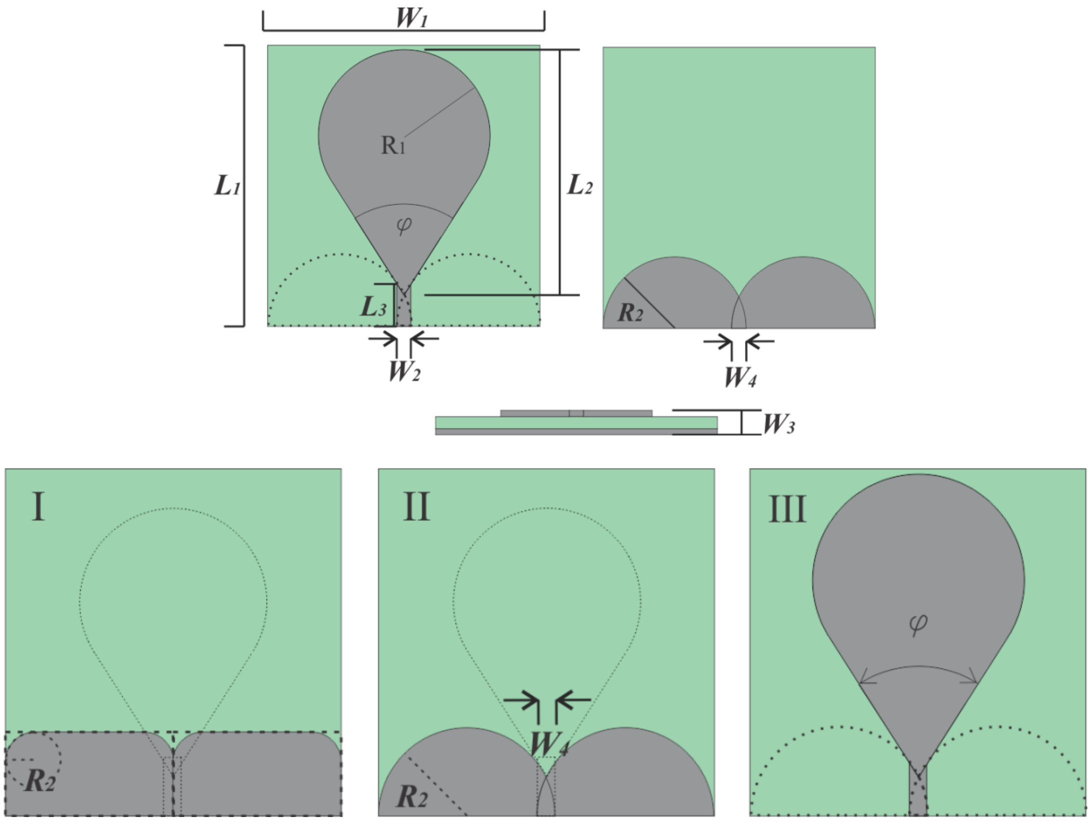

Figure 4:VSA MIMO unit cell and stages of the parametric study

Table 3: 2×2 MIMO results with VSA

Metric	**Value**
Unit size	65 mm × 65 mm
Operating range	2.73–43.38 GHz
Minimum S11	–25 dB @ 10 GHz
Isolation S12	Better than –13.32 dB
Plane type	FR4, single-layer PCB

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3. Simulation and Implementation

The validation of the electromagnetic performance of Volcano Smoke Antenna (VSA) types, in their 3D, 2D, and MIMO versions, was carried out through a combination of numerical simulations and experimental tests. The tools used included CST Studio Suite software for the three-dimensional modeling of electromagnetic structures, as well as measurements in an anechoic chamber to verify the actual response of the prototypes.

3.1. Impedance Matching and VSWR Analysis

In the 3D version, the parametric study of the curved ground plane allowed stabilizing the input impedance around 50 Ω over a wide range. As shown in Figure 5, ground plane thicknesses between 2 and 7.5 mm were evaluated, finding the optimal value at t = 3 mm for θ = 37°, achieving a smooth curve of resistance and reactance.

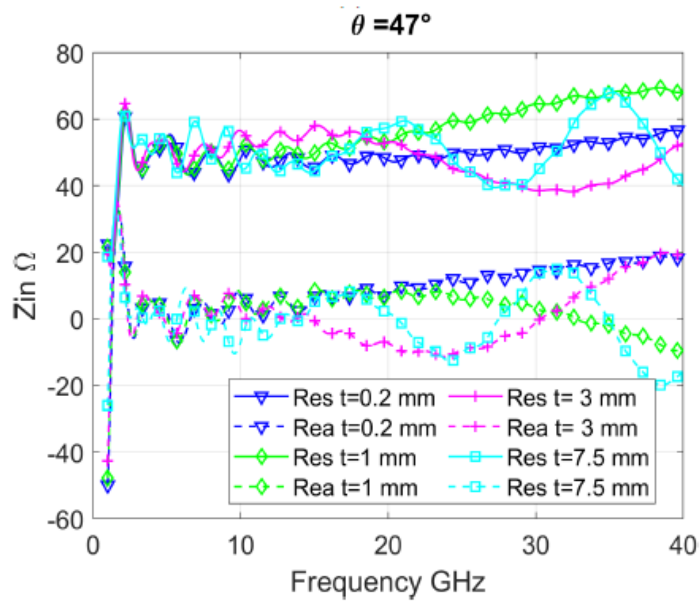

Figure 5: Input impedance (Zin) analysis as a function of ground plane thickness for different configurations.

Table 4: VSWR y Ganancia (3D-VSA)

Metric	Result
VSWR ≤ 2 Range	1.5 – 48.2 GHz
Max. Measured VSWR	2.1
Key Frequencies (Gain)	3.9 GHz (5.4 dBi), 10.7 GHz (5.8 dBi)
Cross-Polarization	< –10 dB (up to 15 GHz)

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3.2 Radiation Patterns and Gain Evaluation

The radiation patterns measured in the anechoic chamber for the 3D-VSA demonstrate vertical linear polarization, with the formation of secondary lobes as the frequency increases (Figure 6). Cross-polarization levels remained below –20 dB in most directions, validating its use in omnidirectional radiation scenarios.

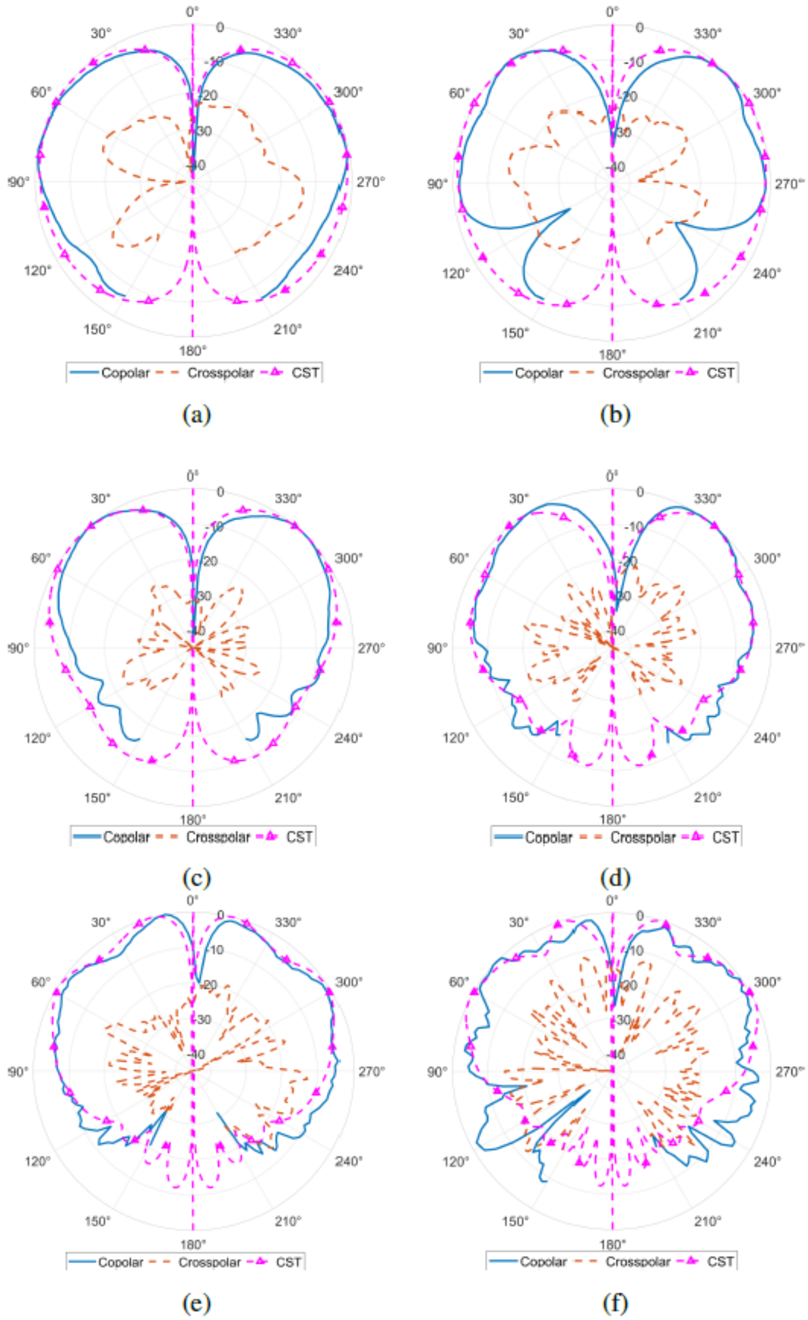

Figure 6: Radiation patterns at 1.7, 3.1, 6.85, 10.6, and 15 GHz for the 3D-VSA

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In the case of the 2D antenna, the radiation pattern maintains a monopolar structure, although it exhibits increased cross-lobe formation due to the loss of one dimension (planarity). The gain analysis shows a range from 1.2 to 6.7 dBi across the entire operating spectrum.

3.3 Isolation in MIMO Configuration

The 2×2 MIMO configuration was implemented on a PCB with four symmetrically positioned VSA elements (Figure 7). The S-parameters were analyzed through full-wave simulations, yielding the following results:

Table 5: 2×2 MIMO System Results

Parameter	Observed Value
Operating Range	2.73 – 43.38 GHz
Minimum S11	−25 dB @ 10 GHz
Isolation (S12)	−13.32 dB (minimum in critical band)
Polarization	Omnidirectional monopolar
Null Lobes	Confirmed at 3.1, 10.6, and 20 GHz

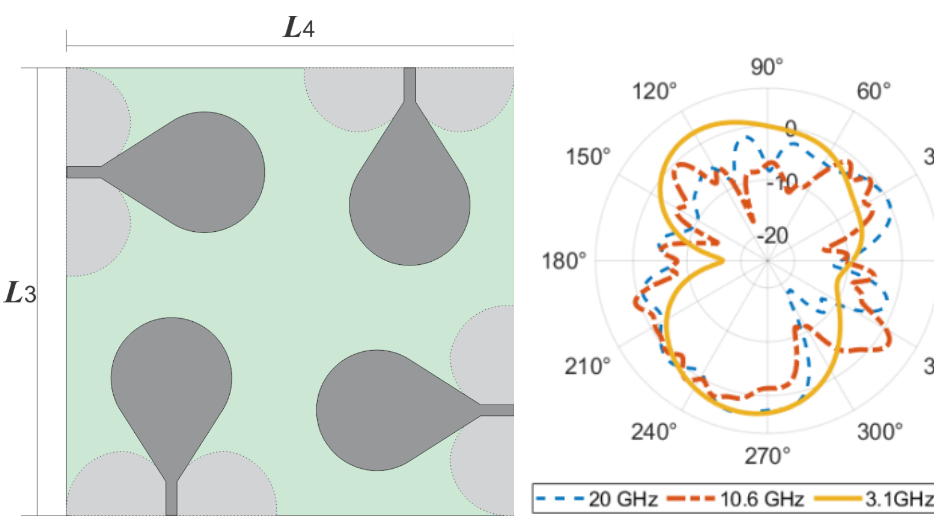

Figure 7: 2×2 MIMO Configuration and Far-Field Distribution at Three Key Frequencies

The MIMO system exhibited controlled electromagnetic coupling, validating its suitability for 5G/B5G applications where wide bandwidth and good spatial channel separation are required.

4. Fabrication and Measurement

The practical implementation of Volcano Smoke Antennas (VSA) in their 3D, 2D, and MIMO versions was carried out using manufacturing processes adapted to their respective geometries.

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This chapter presents the methods employed, materials, and experimental validation results without repeating figures previously used in Chapters 2 and 3.

4.1 3D Printed and Machined Prototypes

The 3D-VSA prototype was initially manufactured using 3D printing in PLA, followed by metallic coating through electroplating. Subsequently, a machined aluminum version was developed to increase structural precision and minimize losses. These prototypes were not presented in previous chapters and are shown in Figure 8.

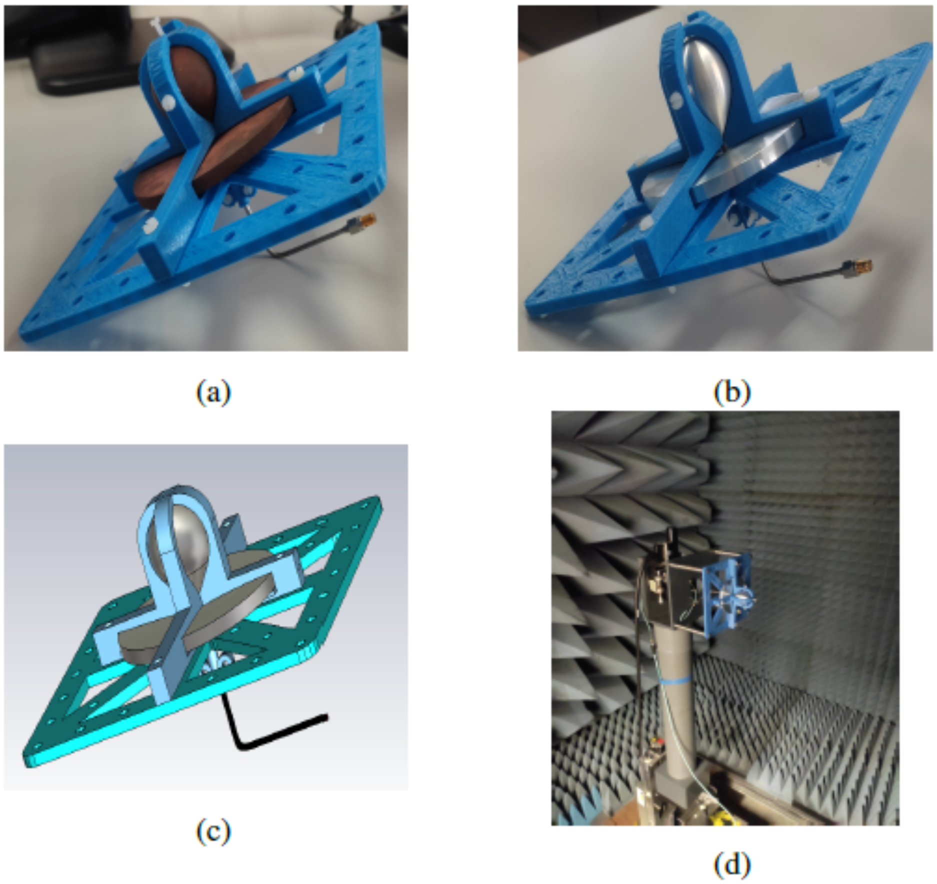

Figure 8: Physical prototypes: (a) 3D printed with metallic coating, (b) machined in aluminum, (c) mounted on a PLA support.

The curved ground plane was shaped following the parametric equation established for k = 1, resulting in variable heights between 3.5 and 7.5 mm. The structure was fed by a coaxial cable with conductors of 0.81 mm (center) and 2.392 mm (outer), with a dielectric constant $\varepsilon r = 1.687$.

4.2 2D PCB Fabrication and Validation

The 2D-VSA model was fabricated on a standard FR4 substrate with a thickness of 1.5 mm, dielectric constant $\varepsilon r = 4.3$, using conventional chemical etching technology. An optimized microstrip-type configuration with tapered lines was used to improve coupling and reduce VSWR across the entire target bandwidth (2.38–49.8 GHz), as shown in Figures 9 and 10.

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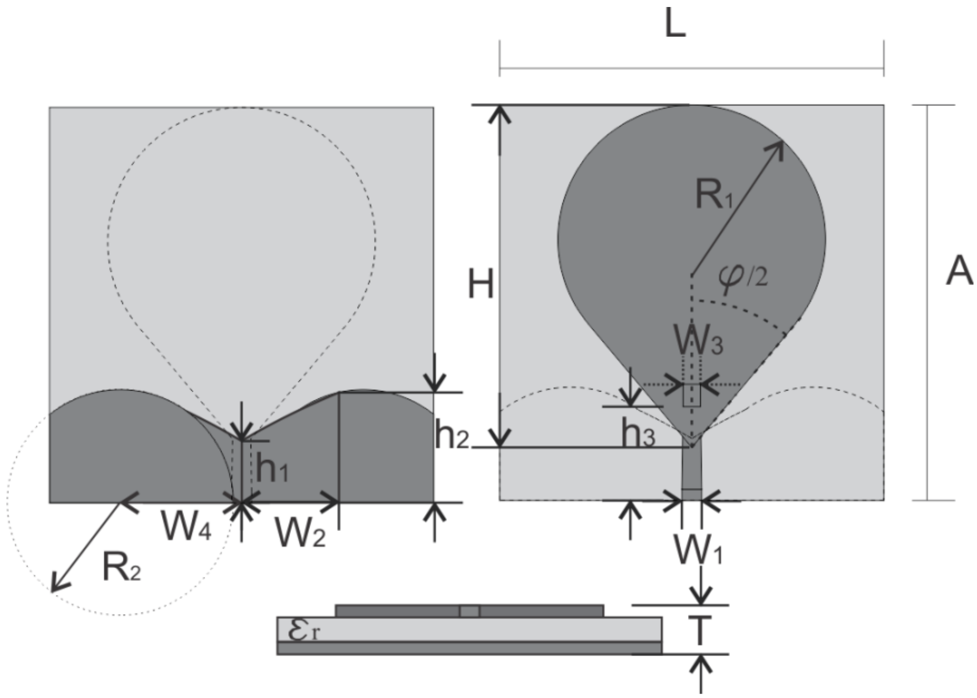

Figure 9: Gain comparison (simulated vs. measured) for the 2D VSA design.

The results obtained surpassed most of the state-of-the-art references regarding size-bandwidth performance, even when compared to structures based on higher-performance substrates such as RT-Duroid 5880.

4.3 MIMO Test Setup and Measurement Results

The MIMO system was assembled on an FR4 board with four VSA elements arranged in a symmetric orthogonal configuration, with controlled spacing (L3 = L4 = 65 mm). The tests focused on measuring the S-parameters, gain, and visualization of null lobes between channels. The measurements confirmed a reflection coefficient S11 ≤ −10 dB across the entire operating range, and a minimum isolation S12 of −13.32 dB, validating the system's capability to operate in high spectral density environments (Fig. 10).

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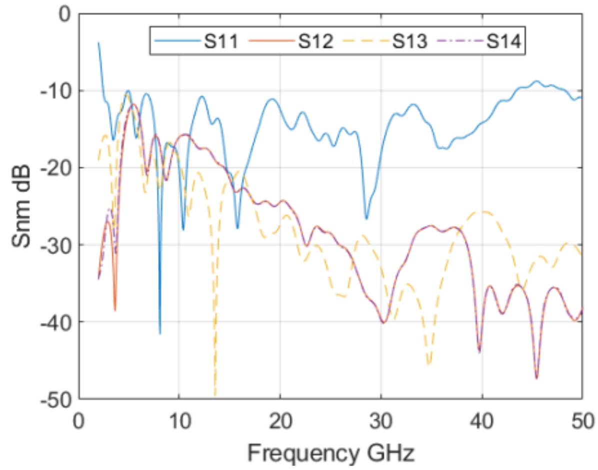

Figure 10: Measured VSWR of the 2×2 VSA MIMO system, showing broadband matching.

The omnidirectional behavior was verified through far-field radiation patterns at key frequencies (3.1, 10.6, and 20 GHz), demonstrating controlled coupling and the appearance of null lobes characteristic of well-decoupled MIMO structures.

4.4 Experimental comparison with the state of the art

To illustrate the competitive advantage of the proposed antennas, Table 6 is presented, comparing their metrics against state-of-the-art references. This table has not been shown previously.

Table 6: Performance comparison (measured) against the state of the art

Reference	BW (GHz)	BW Ratio	Gain (dBi)	Relative Dimension (λ)
[17] (2021)	0.92 – 40	43:1	3 – 6.5	2.1 × 2.1 × 0.46
This work (3D)	1.5 – 48.2	32:1	2 – 5.75	0.52 × 0.52 × 0.26
This work (2D)	2.38 – 49.8	20:1	0.8 – 6.3	0.27 × 0.27 × 0.012

5. Conclusions and Perspectives

This work presented the design, development, simulation, and experimental validation of three variants of antennas based on the Volcano Smoke Antenna (VSA) geometry, aimed at meeting the requirements of emerging 5G and B5G wireless technologies. The studied configurations included:

- A 3D VSA with a curved ground plane and volumetric profile
- A 2D VSA fabricated on PCB for integration in compact systems
- A 2×2 MIMO architecture based on optimized VSA cells

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The results position the VSA antenna family—in its 3D, 2D, and MIMO versions—as a solid, versatile, and efficient alternative to meet the needs of modern communications. Their structural adaptability, wide operating range, and balance between performance and manufacturing cost make these antennas ideal candidates for incorporation into the next generation of global wireless systems.

6. Works Cited

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[2] *2x2 Port Super Wide Band Volcano Smoke MIMO Antenna*, Proceedings USNC-URSI, 2024.

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