Antennas and Propagation Lab (APL)

HEAD OF THE GROUP RESEARCH REPORT

The Antennas and Propagation Lab (APL) is a research group focused on the analysis and design of antennas at frequency bands ranging from UHF to V band, and on propagation measurements and channel modeling for vehicular and wireless systems, with special emphasis on potential mm-wave frequency bands. Antenna analysis and design carried out at APL cover a wide range of applications, e.g. mobile and satellite communications, Wi-Fi, Bluetooth, UWB, IoT or on-body applications.

APL participates in many projects with public funding in collaboration with other Spanish universities, and collaborates with other foreign universities (in Sweden, USA and Finland) as well. From the industrial point of view, APL works with different technological companies and public entities, such as the European Space Agency (ESA), Thales Alenia Space, Huawei or Airbus, and also supports the local technological development through long-lasting links with regional companies like Celestica, MYSPHERA or AITEX.

1.- Project activities

The group activities are developed into four main research lines:

- Application of the Theory of Characteristic Modes for antenna design in different applications (IoT, MIMO, UWB, RFID, WPT, mobile communications, UHF and on-body antennas).
- Gap waveguide technology for the design of antennas and microwave devices in the mm-wave band.
- Development of efficient methods for the electromagnetic analysis of complex structures.
- Propagation measurements and channel modelling.

These research lines are being developed within the framework of different research projects. Next sections describe these projects and the main activities that have been performed during the last year.

1.1.- Ongoing projects

Name of the project: **MAOCOM-6G: Design of MAterials Optimized for an objective function and their application to 6G COMmunication systems.**

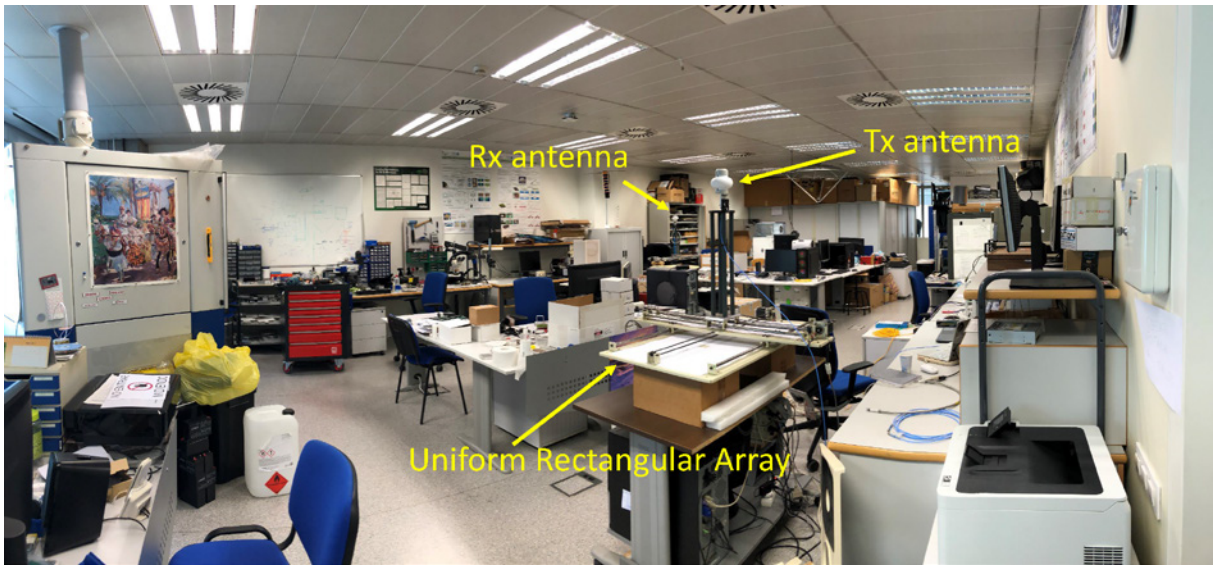
Funding entity and duration: Generalitat Valenciana, 2021-2025.

Summary of the project: The objective of the project is the design of artificial materials (metamaterials or metasurfaces) aimed to exhibit singular or unusual properties when interacting with electromagnetic waves (e.g., reflections, transmissions, and unusual dispersion of the waves). The materials will be designed to operate at the mm-Wave and sub-THz band and will be created using an in-house-developed advanced mathematical optimization code, which will be able to optimize the position of microscopic elements embedded in a macroscopic substrate. These novel materials will be fabricated and tested in the APL facilities at iTEAM. The materials will allow to gain a greater control of the environment of the radio signal propagation, being the objective to create a smart environment around the user for the 6G communication signal propagation.

Name of the project: **A6GMODEL-UPV: Measurement techniques and advanced channel models for the definition of future 6G systems (PID2020-119173RB-C21).**

Funding entity and duration: Agencia Estatal de Investigación. Ministerio de Ciencia e Innovación. MCIN/ AEI/10.13039/501100011033/, 2021-2023.

Summary of the project: The new application technologies envisioned for the next decade make that technical performance requirements of 6G must be higher than those currently achieved by 5G. Requirements of large bandwidths (to be defined, but higher than 400 MHz), high peak data rate (more than 1 Tbps), high user experience rate (on the order of 1 Gbps), density of connected devices (10^7 devices/km^2) and user plane latency (from 25 μs to 1 ms), to mention the most representative, require technical challenges at the PHY layer, but also new improvements in the core network. To overcome these technical challenges, 6G wireless channels need to be thoroughly studied, since the knowledge of the channel is the basis



MmWave channel measurements in a rich scattering environment (A6GMODEL-UPV project).

for designing, optimizing and evaluating the performance of any wireless system. As in 5G, the definition of 6G once again represents a challenge in channel measurements and modelling. The introduction of new enabling technologies, e.g., very large arrays and distributed arrays, and large bandwidths require more complete and robust channel models.

Based on the starting hypothesis, the objective of the project is to develop wireless channel models and generate the channel knowledge required to the definition, standardization, and deployment of the future 6G systems. As indicated in the future vision of channel models in Section 1, important contributions are expected to be made in the three following challenges:

- Definition of a new taxonomy of radio channels.
- Inclusion of very large MIMO arrays and distributed MIMO arrays in the wireless channel model.
- Development of hybrid Quasi-Deterministic channel models.

To achieve the objective of the project, we define a methodology that combines channel measurements, channel simulations, and experimental and theoretical channel modelling.

Name of the project: **RECOMM: REconfigurable antennas for mm-wave broadband COMMunications**

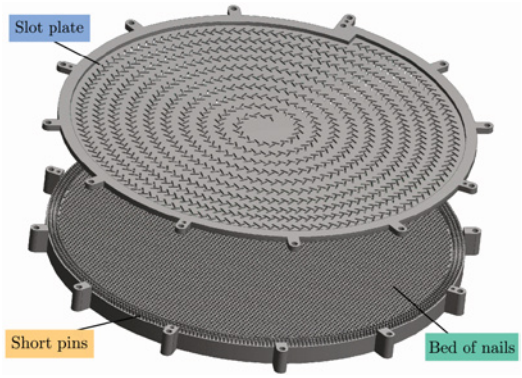
Funding entity and duration: Proyecto PID2019-107688RB-C22 de la Agencia Estatal de Investigación (MCIN/ AEI/10.13039/501100011033), 2020-2022.

Summary of the project: In the coming years, the implementation of broadband communications systems in the millimeter band with global coverage will acquire special relevance. It aims at a convergence of the fixed and mobile services to offer a universal quality of service similar to that of the already mature fiber optic networks. The imminent deployment of 5G networks promises to provide broadband service in sufficiently populated areas, the rest being covered by next-generation communications satellites. The latter allow uninterrupted connection in means of transport (trains, ships, planes) and serve as backup in areas affected by natural disasters or conflict and / or remote zones.

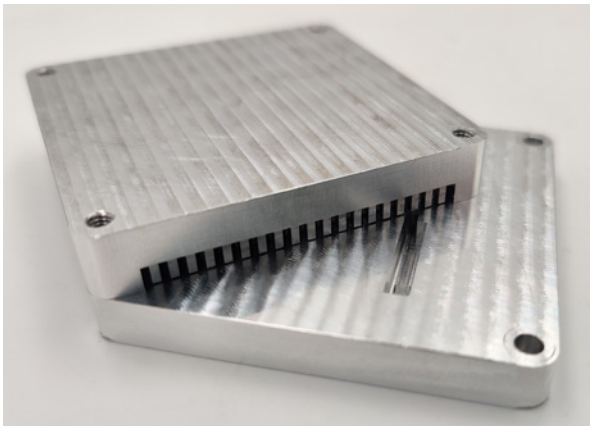
The development of antennas for satellite communications in Ka-band, valid for trains or airplanes, represents a great technological challenge that has not yet been effectively solved by the industry. Very low profile antennas must meet very demanding specifications in terms of gain, secondary lobes, high purity circular polarization, and dual band operation. To these requirements must be added a high degree of reconfigurability, since they must be able to switch polarization in addition to pointing the beam dynamically towards the satellite to compensate for the movement. Also, the deployment of the emerging 5G demands reconfigurable multibeam antennas capable of serving several users simultaneously.

This project addresses the development of new antenna concepts in the millimeter band capable of meeting the demanding needs of these communication systems. Special attention is paid to highly efficient antennas, dual in polarization and / or frequency and capable of reconfiguring their radiation pattern. The control of beam pointing, maintaining the flat character of the antenna, is one of the main objectives of the project. The implementation of a low-cost alternative

mechanism to electronic phase shifters opens the door to the development of competitive low-profile terminals. Innovative solutions capable of generating several simultaneous directing beams are also implemented, valid for multi-user and/or multi-path MIMO communications.



RECOMM project: All-metal circularly-polarized radial-line slot-array antenna in Ka-band.



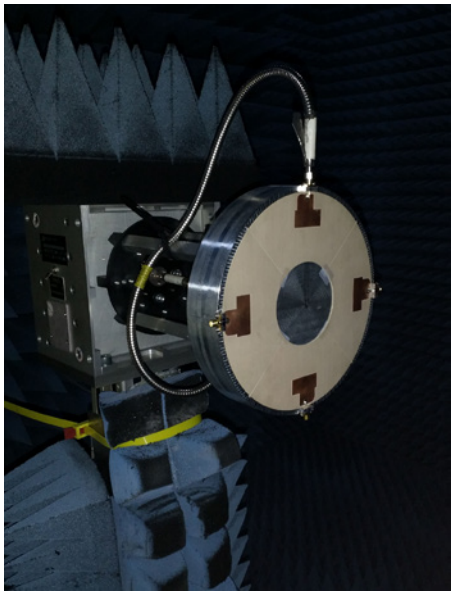
RECOMM project: Novel half-mode groove-gap waveguide for mm-wave device design.

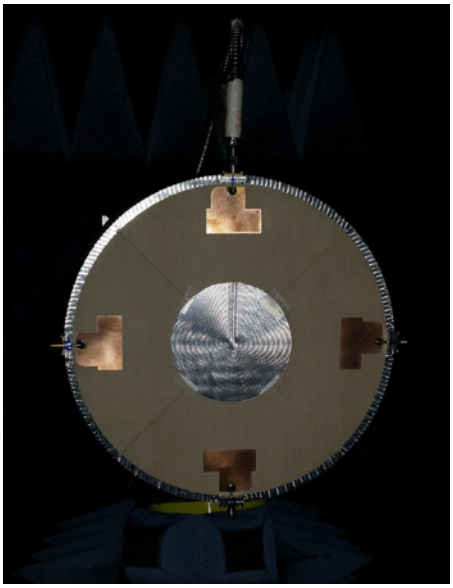
Name of the project: **MUMSYS: MUltimode and Multibeam reconfigurable x-wave antennas for communication and sensing SYStems.**

Funding entity and duration: Proyecto PID2019-107885GB-C32 de la Agencia Estatal de Investigación del Ministerio de Ciencia e Innovación, 2020-2022.

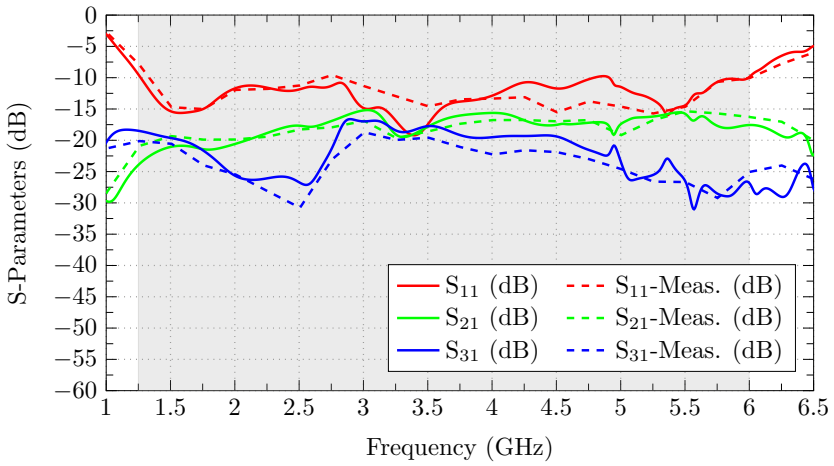
Summary of the project: The main goal of this project is to conceive and develop a new generation of reconfigurable antennas operating into the microwave and millimeter frequency (x-Wave) domains of the electromagnetic spectrum, to face the challenges and requirements of incoming applications. Specifically, the project will focus on various areas:

- Development of an integral equation approach for computational modelling of dielectric mediums. The code presents high efficiency, and it has direct application to the study of dielectric lenses.
- Design of multibeam and mutimode antennas for the sub-6 GHz band, using the Theory of Characteristic Modes. Different antenna designs for 5G base stations with MIMO capability have been developed for the sub-6 GHz band, based on the combined use of multiple feed points and resonant cavities of arbitrary shape.
- Design of a time-multiplexed array, according to new standards for determining the angle of arrival of the waves. Antenna arrays have been developed for angle-of-arrival detection applications and digital beamforming at the LTE-A (1.8 GHz) and 5G (2.6 GHz) bands.
- Fabrication and measurement of a set of LTCC antennas with ceramic materials for the sub-6 GHz band.





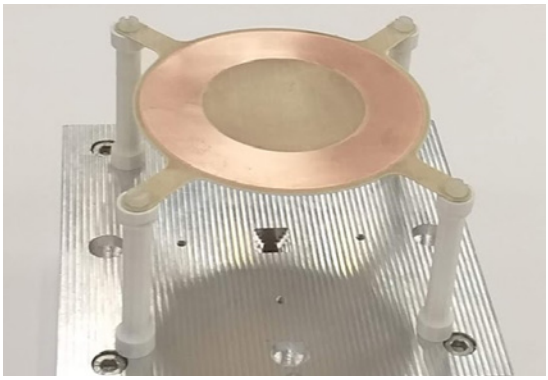
UWB cavity backed antenna for Massive MIMO Systems operating in vehicular environments.



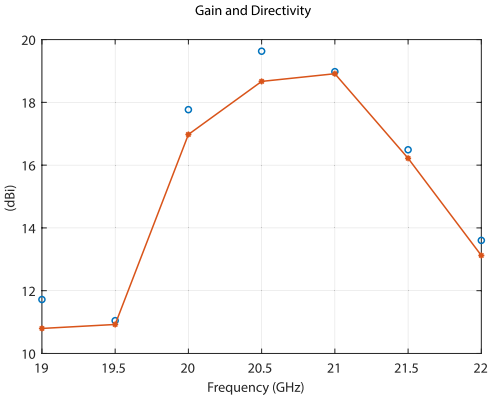
Measured S-parameters (MUMSYS project).

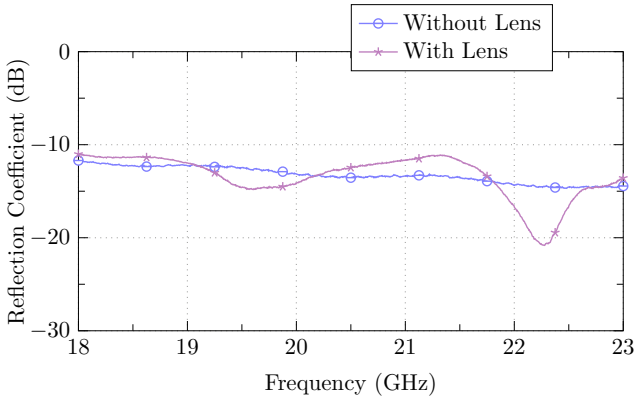
Different models of chip-type antennas have been manufactured with ceramic substrates using Low Temperature CoFired Ceramic (LTCC) technology. The new development features a compact size, good efficiency, does not require a "clearance" zone to be integrated into the PCB, and does not detune when installed on IoT devices and sensors of different sizes.

- Fabrication and measurements of a prototype of a reconfigurable multibeam mm-wave indoor low-cost for 5G and beyond base station, based on metallic planar lenses. A multi-beam multi-feed antenna prototype based on a low-cost flat metallic lens has been fabricated and characterized at UPV. In order to obtain a reconfigurable beam antenna for applications in the 5G millimeter wave band, the focal point is controlled by feeding the lens in different positions. Channel measurement are being performed at UPCT, yielding good results.



Ring shaped metallic lens prototype.





Measured results for the gain, directivity and S_{11} (dB) (MUMSYS project).

Name of the project: ***INNOdeAPI: Innovation and beekeeping development in the region of Murcia.***

Funding entity and duration: ASOCIACIÓN PARA LA INNOVACIÓN Y EL DESARROLLO APÍCOLA. 2022-2023.

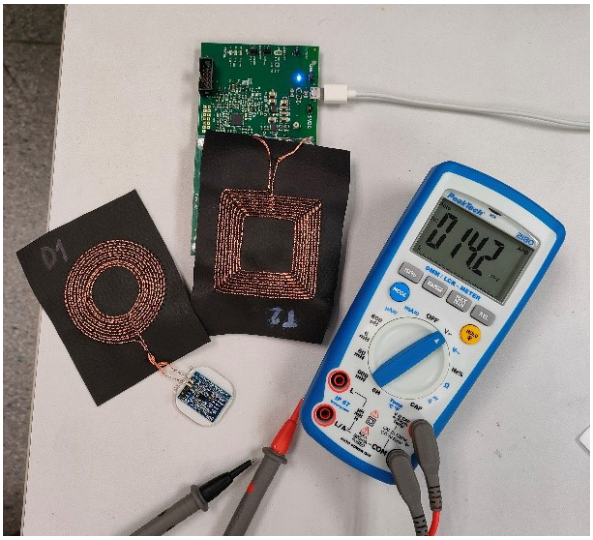
Summary of the project: The aim of this project is to design a complete electromagnetic system for the location of queen bees inside honey combs using Radio Frequency Identification (RFID) at 868 MHz. Small RFID tags are commercially available, but none of them meet the specifications that are needed for this application, so it is necessary to make an specific tag design. The APL research team has designed an external antenna that will be integrated with a proper chip in an RFID tag. This tag will be placed on a queen bee and will allow determining its location in a honey comb. The APL team will also develop a flat planar antenna with circular polarization for the portable reader of the detection system.

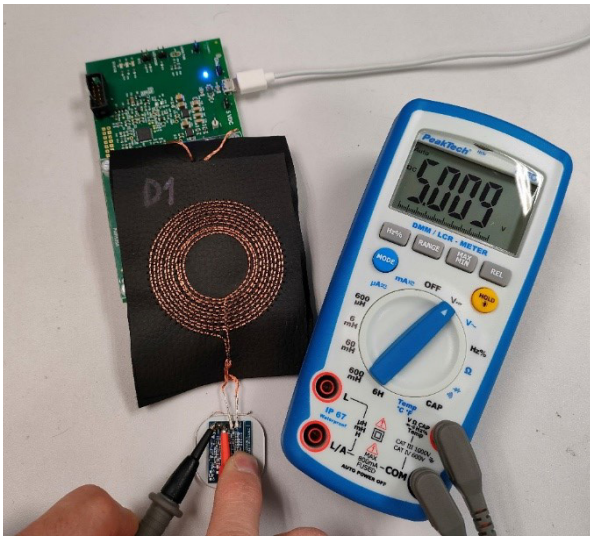
RFID chip antenna used to detect queen bees in a honeycomb (INNOdeAPI project).

Name of the project: **BRODER: INVESTIGACIÓN Y DESARROLLO DE TEXTILES INTELIGENTES EMPLEANDO TECNOLOGÍA DE BORDADO.**

Funding entity and duration: Asociación de Investigación de la Industria Textil AITEX. 2021-2022.

Summary of the project: The objective of this project is to generate different coil designs on a textile substrate using an embroidery machine for the development of wireless energy transmission/reception systems. Specifically, the project contemplates carrying out the following developments: Design of textile loops with the capacity to charge batteries for robots, drones or even electric vehicles, development of smart textiles that obtain the energy necessary for their operation wirelessly, without the need for a battery and development of textile loops capable of feeding environmental sensors using NFC technology.





Set-up used to validate the correct operation of the textile antennas (BRODER project).

2.- Research results

Name of the project: ***FLAT PANEL ANTENNA***

Funding entity and duration: Tampa Microwaves, 8 months

Summary of the project (no more than 300 words per project): The project's purpose was to design two flat panel antennas for TX and RX, respectively, for satellite communications. The panels should provide fixed beam patterns with very good circular polarization (AR<1.5 dB) in the corresponding frequency bands of 19.2 to 21.2 GHz (RX) and 29-31 GHz (TX). Along with the full-size panels design, the project includes the design, fabrication, and measurement of two smaller size panels (16x16 elements array) as a prove of concept.

The project was successfully completed in May 2022. No images of the antennas are shown due to confidentiality.

2.1.- Featured publications

1. Sector Unit-Cell Methodology for the Design of Sub-6 GHz 5G MIMO Antennas, J. Molins-Benlliure, M. Cabedo-Fabrés, E. Antonino-Daviu and M. Ferrando-Bataller, *IEEE Access*, vol. 10, pp. 100824-100836, 2022, **DOI:** 10.1109/ACCESS.2022.3207163.

A novel methodology based on the sectorization of multiple-port cavities with azimuthal symmetry into sector unit cells is presented to design 5G multiple-input multiple-output (MIMO) sub-6 GHz antennas. The methodology divides an N-port cavity antenna into N unit cells and predicts the performance of the N-port design with the analysis of two adjacent cells. This approximation reduces the time and complexity of the simulation of cavity antennas with a high number of ports.

2. Half-Mode Waveguide Based on Gap Waveguide Technology for Rapid Prototyping, M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira and M. Baquero-Escudero, *IEEE Microwave and Wireless Components Letters*, vol. 32, no. 2, pp. 117-120, Feb. 2022, **DOI:** 10.1109/LMWC.2021.3119534.

A half-mode gap waveguide technology for rapid prototyping is explored for the first time. Two devices have been designed and measured for demonstration purposes, a power divider and a curved waveguide. Both devices are constructed from two non-contacting metal pieces: one with half horizontally-polarized groove and the other with a uniform pinned surface, acting as a high impedance surface. These devices stand out for their ease of fabrication and open a horizon for cheaper and more robust microwave designs.

3. High-Efficiency Ka-Band Circularly Polarized Radial-Line Slot Array Antenna on a Bed of Nails, J. I. Herranz-Herruzo, A. Valero-Nogueira, M. Ferrando-Rocher and B. Bernardo-Clemente, *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 5, pp. 3343-3353, May 2022, **DOI:** 10.1109/TAP.2021.3137376.

A half-mode gap waveguide technology for rapid prototyping is explored for the first time. Two devices have been designed and measured for demonstration purposes, a power divider and a curved waveguide. Both devices are constructed from two non-contacting metal pieces: one with half horizontally-polarized groove and the other with a uniform pinned surface, acting as a high impedance surface. These devices stand out for their ease of fabrication and open a horizon for cheaper and more robust microwave designs.

4. Single-Layer Sequential Rotation Network in Gap Waveguide for a Wideband Low-Profile Circularly Polarized Array Antenna, M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira and B. Bernardo-Clemente, *IEEE Access*, vol. 10, pp. 62157-62163, 2022, **DOI:** 10.1109/ACCESS.2022.3182336.

A low-profile circularly-polarized sequential rotation fed 4x4 array antenna working in Ka-band is presented. The particularity of the antenna lies in its single-layer sequential rotation feed network using a combination of groove and ridge gap waveguides. The basic radiating element is one slot loaded by a simple coffee-bean-shaped parasitic element on top. Experimental results show an antenna matching below −10 dB in a 13.6% bandwidth and a measured axial ratio below 1.3 dB in the desired band.

5. Antenna Element Design Using Characteristic Mode Analysis: Insights and research directions, J.J. Adams, S. Genovesi, B. Yang, E. Antonino-Daviu. *IEEE Antennas and Propagation Magazine*, vol. 64, no. 2, pp. 32-40, April 2022, **DOI**: 10.1109/MAP.2022.3145718.

This paper provides a comprehensive review of recent applications of characteristic mode analysis (CMA) to innovative antenna element designs, including multiport, circularly polarized, wideband, reconfigurable, and dielectric resonator antennas (DRAs). Emphasis is placed on the interpretation of the characteristic modes (CMs) for those unfamiliar with the method and physical insights gained from the characteristic eigenvalues and eigenvectors of an antenna. In addition, we review CMA-based design strategies and specific design examples that highlight the application of CMA to various types of antennas. Ultimately, this article seeks to demonstrate the value of CMA-based design insights for antenna engineering and look toward promising new research directions for CMA and antenna research.

6. Wireless Channel Analysis Between 25 and 40 GHz in an Intra-Wagon Environment for 5G Using a Ray-Tracing Tool, J. Pascual-Garcia; L. Rubio; V. M. Rodrigo Penarrocha; L. Juan-Llacer; J.M. Molina-Garcia-Pardo; C. Sanchis-Borras; J. Reig, *IEEE Transactions on Intelligent Transportation Systems,*

2022, **DOI:** 10.1109/TITS.2022.3199159.

In this work, the wireless channel in an intra-wagon environment is thoroughly analyzed using simulations performed with a ray-tracing tool calibrated and validated with wideband measurements. Thanks to the accurate ray-tracing tool the main replicas are identified in different typical user equipment-access point positions; the contribution of each propagation mechanism to the total power is extracted; and the angular spread in azimuth and elevation for the direction of arrival and departure are obtained. This analysis is performed in the frequency range from 25 to 40 GHz, where spectrum for several 5G bands has been already allocated.

7. A Comparison Between Concentrated and Distributed Massive MIMO Channels at 26 GHz in a Large Indoor Environment Using Ray-Tracing, J. R. Perez; L. Valle; O. Fernandez; R.P. Torres; L. Rubio; V.M. Rodrigo Peñarrocha; J. Reig, *IEEE Access,* vol. 10, pp.65623-65635, 2022, **DOI:** 10.1109/ACCESS.2022.3184450.

In this paper, a comparative analysis between concentrated and distributed massive multiple-input multiple-output channels (C-mMIMO and D-mMIMO respectively), in an indoor environment using ray-tracing (RT) in the 26 GHz band is presented. The comparison is carried out in a realistic scenario consisting of a floor of a large building. The simulations emulated the up-link channel in an indoor cell in the framework of a time division duplex (TDD) - orthogonal frequency division multiplexing (TDD-OFDM) system. The results show that the D-mMIMO channel outperforms the C-mMIMO one from the point of view of their behavior in broadband as well as in terms of the obtainable capacity.

8. Millimeter Wave MISO-OFDM Transmissions in an Intra-Wagon Environment, C. Sanchis Borras; J.M. Molina-Garcia-Pardo; L. Rubio; J. Pascual-Garcia; V.M. Rodrigo Peñarrocha; L. Juan Llacer; J. Reig, *IEEE Transactions on Intelligent Transportation Systems,* vol. 22, Issue: 8, 2021, **DOI:** 10.1109/TITS.2020.2983028.

In this paper, the maximum achievable throughput is analyzed in the intra-wagon channel when multiple-input single-output (MISO) and orthogonal frequency division multiplexing (OFDM), MISO-OFDM, techniques are used. This analysis is performed from real wideband propagation channel measurements at 28 and 37 GHz, two potential frequency bands to deploy the future 5G wireless communications networks. Four different scenarios in terms of the access point (AP) and user equipment (UE) positions inside the wagon have been considered, using 4 and 8 antennas at the AP. These results provide useful insight to better understand the intra-wagon channel properties and deploy the future 5G wireless networks in this particular scenario at mmWave frequencies, where high-data-rates are expected to support different types of digital applications.

9. Fading Evaluation in Standardized 5G Millimeter-Wave Band, T.R. Rufino Marins; A.A. Dos Anjos; C. R. Nogueira Da Silva; V.M. Rodrigo Penarrocha; L. Rubio; J. Reig; R.A. Amaral De Souza; M. Daoud Yacoub, *IEEE Access,* vol. 9, pp. 67268 - 67280, 2021, **DOI:** 10.1109/ACCESS.2021.3076631.

This paper reports on a thorough measurement campaign conducted in an indoor environment characterized by rich-multipath scattering, a part of a modern building, with floor and ceiling constructed of reinforced concrete over steel plates with wood and plasterboard-paneled walls. Particularly, measurements have been performed in a variety of scenarios, under line-of-sight (LoS) and non-line-of-sight (nLoS) conditions, for a wide range of frequencies, namely from 25 to 40 GHz.

10. Novel Asymmetric T-Shaped Radiating Element for Circularly-Polarized Waveguide Slot Arrays, J. I. Herranz-Herruzo, M. Ferrando-Rocher, A. Valero-Nogueira, B. Bernardo-Clemente, *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 11, pp. 7452-7461, Nov. 2021, **DOI:** 10.1109/TAP.2021.3076277.

An all-metal T-shaped radiating element is conceived with the aim of replacing the usual rectangular slots and attaining all-metal circularly polarized arrays. The design of resonant shunt arrays has been addressed for validation purposes. The experimental results of two sample linear arrays at 30 GHz demonstrate the design accuracy and manufacturing reliability, reporting an axial ratio below 2 dB within a bandwidth of 1.9 GHz and a peak efficiency around 98%.

11. Switchable T-Slot for Dual-Circularly-Polarized Slot-Array Antennas in Ka-Band, M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira and B. Bernardo-Clemente, *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 10, pp. 1953-1957, Oct. 2021, **DOI:** 10.1109/LAWP.2021.3101156.

Two slotted array antennas working in Ka-band with switchable circular polarization capability are presented. Radiating elements in both antennas are reconfigurable T-shaped slots, forming a linear 1x10 and a corporate-fed 2x2 array, respectively. Good polarization purity is achieved for both polarization senses and in both prototypes. The fundamental contribution of this letter is to propose a simple mechanism to switch the circular polarization sense in a low-cost, low-profile, and high-efficient antenna.

12. Low-profile UWB antenna with unidirectional radiation pattern analyzed with the theory of characteristic modes, C. R. Peñafiel-Ojeda, M. Cabedo-Fabrés, A. Llanga-Vargas, M. Ferrando-Bataller, *AEU - International Journal of Electronics and Communications*, vol. 142, 202.

This paper presents a low-profile Ultra Wide Band (UWB) antenna with polarization diversity for new 5G base stations. The antenna consists of a metallic ring capacitively fed with four circular monopoles and reinforced with a cylindrical cavity to generate a unidirectional radiation pattern. The Theory of Characteristic Modes is used to analyze and explain the behaviour of the proposed antenna excited with differential feeding configurations.

13. Responsivity enhancement of a strained silicon field-effect transistor detector at 0.3 THz using the terajet effect, I. V. Minin, O. V. Minin, J. Salvador-Sánchez, J. A. Delgado-Notario, J. Calvo-Gallego, M. Ferrando-Bataller, K. Fobelets, J. E. Velázquez-Perez and Y. M. Meziani, *Optics Letters*, vol. 46, n. 13, pp.3061-3064, 2021.

The enhancement of responsivity by more than one order of magnitude of a silicon-based sub-terahertz detector is reported when a mesoscopic dielectric particle is used to localize incident radiation to a sub-wavelength volume and focus it directly onto the detector. A strained-silicon modulation field-effect transistor is used as a direct detector on an incident terahertz beam at 0.3 THz. A systematic study in which Teflon cubes are placed in front of the detector to focus the terahertz beam is performed.