UNICO I+D Project
6G-INTEGRATION-4

E09-6G-INTEGRATION-4

5G energy feed design

Abstract

This deliverable contains the conceptual design of the HAPS 6G-INTEGRATION-4 5G Tx/RX system. This document presents the initial research and development to develop a simulated integration energy payload for 6G-INTEGRATION-4 platform. Defines the main I/O needs and CONOPS of the payload energy requirements.

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Reviewers	Eduardo Arca Ramirez (Edair Technologies)
	Daniel Segovia Vargas (UC3M)

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List of Acronyms

NSR: Northern Sky Research

IFC: InFlight Connectivity

NGA: New Generation Networks Accesses

FTTH: Fiber To The Home,

OTT : Over-The-Top

NSA: Non Stand Alone

IoT : Internet of things

B5G: Beyond 5G

HAPS: High Altitude Platform System

CIR: Carrier-To-Interference Ratio

DBF : Digital Beam Forming

ITU: International Telecommunication Union

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Resumen Ejecutivo

El objetivo principal es verificar y justificar el novedoso concepto mediante el desarrollo y fabricación en varias fases del dispositivo reducido suficientemente representativo que consta de:

- Conjunto de antenas con un número reducido de elementos radiantes con sus cadenas frontales de RF asociadas
- El sistema de control que debe permitir la conformación del haz.
- Soporte mecánico asociado y piezas auxiliares.
- El terminal puramente electrónico que proporciona una amplia cobertura a un precio competitivo en comparación con un sistema de antena activa totalmente plano

Razonamiento en cuanto a los resultados del proyecto y posibles salidas comerciales al mercado aeronáutico los resultados del proyecto pueden diverger hacia dos tipos de terminales, que se pueden agrupar de la siguiente manera:

- El terminal electromecánico que combina un barrido electrónico reducido con un movimiento mecánico competitivo en costes con los sistemas actuales basados en antenas parabólicas o paneles.
- El terminal puramente mecánico a un coste inferior respecto a los sistemas utilizados actualmente.

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Executive Summary

The main objective is to verify and justify the novel concept through development and manufacturing in several phases of the sufficiently representative reduced device that consists of:

- Antenna array with a reduced number of radiating elements with their associated RF front chains
- The control system that must allow beam shaping
- Associated mechanical support and auxiliary parts
- The purely electronic terminal that provides cost-competitive wide coverage compared to a totally flat active antenna system

Reasoning regarding the project results and possible commercial outlets to the aeronautical market the project results can be splitted into two types of terminals, which can be grouped as follows:

- The electromechanical terminal that combines reduced electronic scanning with mechanical movement that is cost-competitive with currently used systems based on satellite dishes or panels.
- The purely mechanical terminal at a lower cost compared to the systems currently used.

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1. Introduction

HAPs may exploit millimetre-wave spectrum by supporting multi-cell architectures. The overall data capacity is governed by the properties of the antennas which serve the cells. Optimum coverage is expected when each antenna radiation pattern is tailored to its respective cell, but this leads to a bulky payload. In contrast, this document shows how a payload based on multi-beam spherical lenses, which have wide-scan properties but also offer circular beams, can give comparable performance while offering a much more compact payload. Models for spherical lens radiation patterns are presented which include the effect of the primary feed beamwidth. This allows a comparison of aperture diameter, sidelobe level, and the resulting co-channel interference, from which the performance and relative mass of different antenna payload types may be estimated.

2. Technical characteristics

Airborne Antenna for In-flight Connectivity idea is that the higher the height, the more power and therefore more weight, since you cover more surface area and you are further away, so we assume that the antennas should suffer a variation of this type depending on the working altitude of the platform:

- 20Km-20Kw-100Kg
- 10Km.10Kw-50Kg
- 5Km-5kw-10Kg

Obviously, they are very approximate and preliminary numbers but, assuming a phase array, because depending on the altitude and the surface to be covered, which does not only depend on the altitude, since there will be other conditions such as beam opening, etc.

2.1. Target Service and Market

Satellite services and products associated with mobility platforms (aircraft, ships, trains, vehicles, etc.), manned or unmanned, constitute an opportunity and a growing business with significant growth prospects, both in the civil sector and in sectors such as defense/security/emergencies/NGOs,...

Figure 2.1-1 Expectativas de negocio asociado a soluciones satélite en movilidad (fuente: Intelsat)

However, current terminal technologies are far from meeting user expectations in terms of cost, performance, configuration complexity, size/weight, etc. The mechanical solutions deployed, for example, in major airlines, come from mechanical designs in which the radiating element is positioned by motors to find the appropriate position.

This type of design concept is very little useful for aeronautical operations and the market demands more compact and powerful solutions that do not entail a penalty in the aerodynamic cost and therefore in the cost and carbon footprint due to the greater expenditure on fuel. Additionally, the deployment of medium/low orbit satellite constellations cannot work with these mechanical solutions. For this reason, the industry has been investing significant sums in purely electronic solutions for years (Phasor, Kymeta, Alcan, GILAT,...) but the results are still poor and there are no truly marketable products. This is due to the complexity and high cost of purely electronic solutions, apart from still unsolved problems for aeronautics regarding energy consumption and resistance of materials to working and ambient temperatures in environments in the upper layers of the atmosphere.

There is therefore an unmet demand and a clear opportunity to explore an alternative antenna concept (source NSR 2019), based on lenses, that is positioned as a technology capable of solving some of the challenges and shortcomings faced by the industry, especially reducing the cost of manufacturing and configuration, to achieve competitive products in price and with more than adequate performance, aimed at satisfying in the first instance the demands of the aeronautical sector. These demands will focus on increasingly smaller and more powerful terminals that allow greater connectivity to aircraft in both civil (commercial) and military fields and increase the capabilities of a sector in broad development such as long-range unmanned systems.
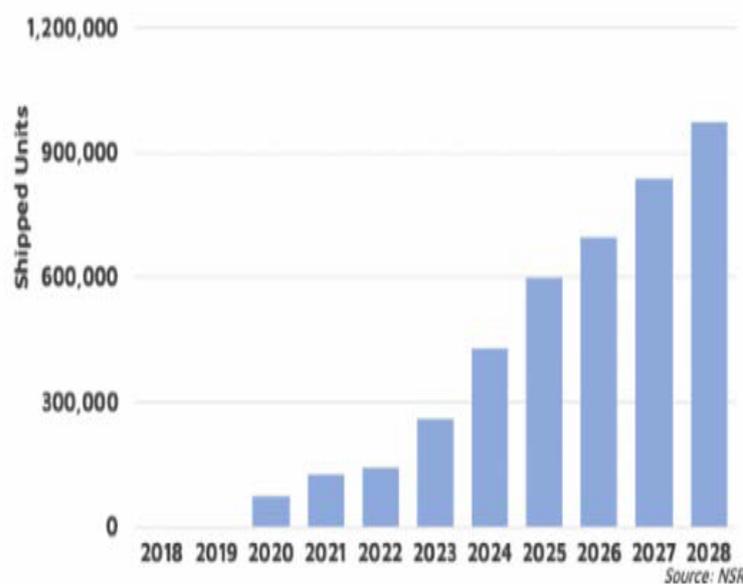
Figure 2.1-2 "Flat PannelAntennas" growth expectations (NSR 2019)

The objective is to develop and prototype the next generation of low-profile airborne antennas that will be used for In-Flight Connectivity in the horizon 2022-2025. This will also demonstrate that the use of electronically steering can meet the stringent requirements of commercial aircraft connectivity, while bringing significant benefits such as reduced maintenance, low drag and weight. This document describes the design and prototyping and testing "on ground" of an airborne antenna highly integrated into the fuselage based on lenses technologies. It is TRL 4-6 demonstrators tested into a satellite operator´s network. In-Fight Connectivity is becoming a must for commercial airlines over the world.

Being able to offer hi-speed Wi-Fi service to passengers, in different flavours and service models, is a priority for commercial airlines. Servicing bandwidth-hungry passengers becomes a key issue for the airline industry customer experience model. In April 2019, NSR forecasted inflight connectivity (IFC) to be a $36 B market over the next decade (source SkyHigh Economics. LSE. 2018). "All major airlines are involved in an IFC program and connected aircraft is seen as inevitable". Passenger expect more and more a seamless service whether on-board or at land.
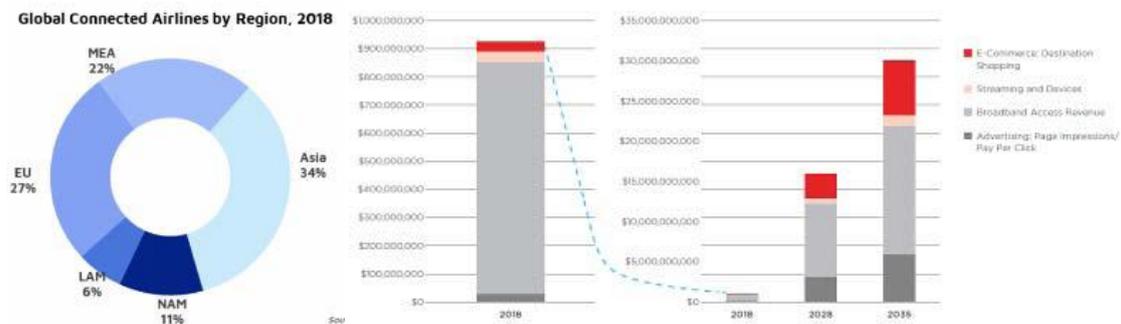
Figure 2.1-3 Forecast airline broadband-enabled ancillary revenue: 2018, 2028, 2035.
(Source: SkyHigh Economics. LSE. 2018)

Satellite is the main choice for most airlines due to one single reason: coverage. However, it does not come without problems, cost being the most significant:

- Cost of installation, both in terms of cost of equipment and time required and also system maintenance
- Higher cost per Mbyte

In addition, heavier and bulkier satcom equipment creates additional drag, which translates to fuel consumption, a key performance indicator for most commercial airlines. Industry is working hard to overcome these hurdles. To understand potential solutions, a brief overview of satellite solution for aircraft is necessary. A satellite-connected aircraft includes the following modules or components:

- Antenna or radiating element, installed on top of the aircraft, covered by a radome. Antenna is a key element impacting connectivity performance
- Transmission / reception equipment, including modem
- Control and tracking system
- Wifi distribution network inside aircraft
- Ground infrastructure

Mentioned systems can be seen in the following infographic (source New York Times)
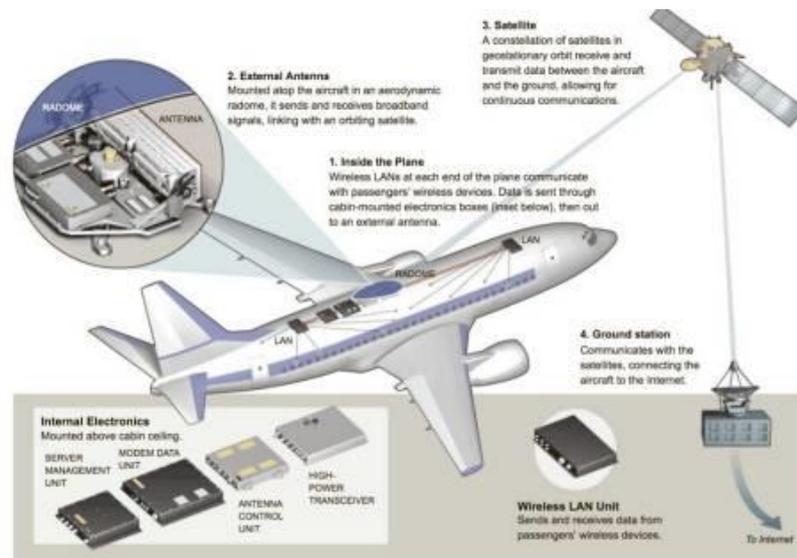
Figure 2.1-4 Satellite-connected aircraft components

Aeronautics industry presents a clear set of requirements that create a significant technology challenge for solution providers. Most of these requirements must do, directly or indirectly, with system Total Cost of Ownership (TCO)

- Maximise performance vs size (footprint on fuselage x antenna height)
- Maximise performance vs aircraft geographical location (i.e. avoid performance decrease in regions like Equator or in extreme latitudes)
- Minimise drag, thus reducing fuel consumption
- Minimise hardware cost
- Minimise installation cost
- Minimise installation time, qualification and testing requirements, for retrofit scenarios (i.e. minimise aircraft down-time)
- Minimise potential maintenance problems, maximise MTBF
- Minimise power consumption
- Maximise spectral efficiency, bits per hertz in order to optimise satellite service cost
- Beam / Tracking agility o seamlessly manage roaming and transitions between satellite beams (in case of GEO HTS)
- Seamlessly manage switching between satellites (in case of MEO/LEO constellations)
- Multi band capability desirable (Ka/KU, ...)
- Comply with regulation, specifically ASI (Adjacent Satellite Interference)
- Perform under severe environmental conditions (DO-160)

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Antenna is a key solution element, which has significant impact in several, if not all, above-mentioned requirements. Thus, industry is making significant investments to design adequate antenna solutions. A clear evolution is established, which is summarized in the following figure:

Figure 2.1-5 Satellite-connected aircraft antennas evolution

2.2. State-Of-The-Art of Satcom Electronic Scanned Antennas and Key Players

EDAIR has agreements with the main international satellite operators such as Inmarsat and Viasat for the installation of their equipment on aircraft, mainly equipment from Honeywell and Cobham. Such equipment, which is part of the current state of the art, has certain conditions that make its acquisition, operation and installation cost ineffective in commercial passenger aircraft and its implementation in smaller, regional, military and unmanned aircraft is very complex, requiring these to more specific and expensive solutions.

Figure 2.2-1 Typical antennas equipment in use

However, there are developments of flat or shaped antennas with electronic beam pointing, but the current state of the art does not cover the current needs for bandwidth, low profile and low terminal cost. Active antennas with purely electronic beam scanning are expensive systems and to date no viable system has been implemented in civil aeronautical communications. It should be noted that .

mechanical terminals are still those exclusively used in satellite communications from an aircraft with maintenance problems, high profile and pointing miscalibration that make them ineffective.

The other antenna options used are based on the use of reflectors or passive panels extended in the horizontal plane in order to reduce the wind load (Viasat, Cobham, Qest etc.). The last type of antennas presents the equator's problem having great difficulty to comply with the regulations imposed by satellite service operators.

Flat antennas with electronic scanning are the solution that several companies are betting on in order to achieve an accessible product for the satellite communications market from different land and aeronautical mobile platforms.

Boeing, Gilat, Phasor Solution, Mitsubishi have been for a long time involved in the development of these systems with significant investments, announcing a real implementation close by that after years and huge investments has not yet come. To date, there has been no commercial impact of these systems on the market, quite the opposite because systems with motorized antennas continue to monopolize the majority of the market, such as the Honeywell JET WAVE terminal (attached image).

An alternative concept promoted by the company GoGo has a strong presence in the aeronautical market with its system developed by the American company ThinKom offering a flat and very low profile system based on the patented technology called VICTS. In reality, it is a purely mechanical antenna system whose amplitudes and phases on the radiating aperture are adjusted by means of a subsystem whose geometry is changed by motors. The problem it presents is its size, cost and maintenance since we continue to base the pointing on motorization.

The American company Kymeta with its proposal based on metamaterials supported by Microsoft, which arose very strong interest, has recently withdrawn from the aeronautical world, after its technology was declared unsuitable by the FAA after altitude and heat tests with the boeing 787. Kymeta is now trying to promote its solution for maritime applications.

The biggest problem with flat and purely electronic systems are their costs associated with the RF part and materials. Despite significant progress in MMICs, the investment remains high given that hundreds or thousands of RF front-ends need to be integrated in a very small volume. Furthermore, the control subsystem that must form the beam becomes very complex.

On the materials side, they are expensive and have erratic behaviour with changes in temperature, which makes them not reliable solutions for aeronautics. The other weak point of this concept is the poor radiation performance if the aim is to shape the beam at very low angles. In order to increase angular coverage, it is intended to locate several of these systems on the fuselage, which increases the total cost even more.

The objective of this document is to develop a technological demonstrator (TRL 4-6) and a patent that allows us to solve the current satellite communication problems of the medium and long commercial distance aeronautical segment and to include said capacity in smaller segments such as regional and even in HAPS that allow non-line-of-sight operation, which would allow this segment to drastically expand its activities and market. In addition, all of this would be undertaken at all of this at an affordable cost and with an affordable operation and maintenance cost for this type of operations.

In a second phase of the project, once the demonstrator prototype has been chosen EDAIR to develop and patent this technology. There will be companies focused on manufacturing the component as well as investors for its commercialization. The experience in developing terminals gives us support in the project up to the point of prototype development and validation, while companies such as Sener and Everis, with which we have already proposed this solution, would be potential partners in the next

phase with the industrialization and integration of the component, EDAIR will remain, once the prototype technology has been patented and certified, as the installer and owner of the solution.

It is not the objective of this project to develop a terminal manufacturing plant since this technology already exists and in a production phase the relevant agreements can be reached for the industrialization of the product. The objective of this first phase of the project is to validate the technology through the development of a demonstrator prototype of the same. Hence EDAIR in the RF design part, conform a flexible and cost-controlled cooperation scheme for a prototype development with a low cost and in a timely way that allows maintaining the interest of the market.

The technology of electronic pointing antennas based on the phase change of the elements that make up the panel has been used only in the military field due to their high cost, which leads to different opinions about the commercial viability of the antennas themselves. Until now, they have entailed such high costs that their use has been limited to the military field. However, two companies, Phasor, Inc and Kimeta Corp., are developing new technologies and approaches to bring these low-profile antennas to market. Recently seattle-based Kymeta has focused on Ka-Band frequency and the use of metamaterials, a new and not yet commercially proven technology. Phasor, a Washington DC-based company, is in the final stages of completing a five-year development to bring this technology to market in Ku Band, using a technology called conventional MMC in an innovative way.

Phasor technology uses a patented microprocessor (ASIC) design, in which each ASIC is linked to a radiating "element" and these elements form panels that harmonize function through an array, creating an electronically adjustable beam antenna. Additionally, since this system immediately converts signals to digital, the architecture supports unlimited scalability, without the losses associated with conventional analog systems. The result is a high-performance, economical and highly scalable flat Ku-band antenna. Phasor has announced successful test results. It will be launched in Ku band and they have set plans to expand to other frequencies including Ka and X bands. The focus of the Phasor solution is aimed at a luxury yacht and train market. Recently, they have established a collaboration with the service provider GoGo SOTM in order to be used for aerial applications.

Figure 2.2-2 – Phasor – Electronic scanning flat antenna

Kymeta's metamaterials technology is a novel, patented implementation of a new field in materials science. Effectively, metamaterials "bend" radio waves to achieve electronically steered antenna functionality. This, together with a polarizing "film" covering the panel, allows for SATCOM connectivity.

Kymeta currently has development contracts with Inmarsat and O3B, has several major investors and has plans to make satellite broadband relevant in different types of markets. They have also recently announced successful tests, however, many experts have expressed concern that this technology is

more difficult to implement at lower frequencies, as it could have limited scalability and be affected by extreme temperature variations (as is often the case in the airplanes). Additionally, with Kymeta's technical approach, linear polarization (typically required in Ku Band services) can be difficult to achieve. While Kymeta has primarily focused on developing a Ka-Band antenna, the company may, at some point, also seek to develop and introduce a Ku-Band product. Like Phasor, Kymeta is also targeting the luxury yacht market and land mobile platform application. In 2017, Panasonic Avionics canceled its intention to implement the Kymeta solution in airborne applications after demonstrating that this technology was not mature enough for this.

As the Ku Band is mature in the main markets and the main satellite operators (Intelsat, Telesat, SES and Eutelsat) plan to launch services in this Band with spot beam satellites, Phasor enjoys of the opportunity to be the first in the sector with this satellite technology, an advantage that could result in a significant growth opportunity for the company.

Figure 2.2-3 – Kymeta Metamaterial electronic pointing antenna

Panasonic Avionics and Boeing, on the other hand, have teamed up to develop a new lightweight antenna system that will give airlines the ability to provide in-flight connectivity to passengers. The terminal profile is 6.8 cm high and is the thinnest and lightest available solution (63.5kg). It has been announced that the system was expected to be available for commercial installation in the fourth quarter of 2024. As of today, there are no updates available on actual flight testing and implementation of this system.

Figure 2.2-4 – Boeing Phased array antenna

SD AvionicsTeams powered by QEST (light aircraft panels) Hardware manufacturing division SatcomDirect (SD Avionics) has partnered with Germany-based QEST to develop a flat antenna that can be installed on medium-sized light commercial aircraft to provide connectivity broadband. The antenna is a flat and electronic pointing phased array antenna.

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Figure 2.2-5 – SD flat panel antenna in development together with Qest.

The announcement of the satellite constellations that will be compatible, both geostationary and LEO and MEO, is pending. The design of this antenna is scalable and modular and will be adjusted to the size and shape of the fuselage of the aircraft where it is shipped.

Gilat has developed an innovative fully electronically steered phased array antenna (ESA/PAA) technology for mobile satellite communications. The antenna is extremely thin (low profile) and electronically directs the transmit and receive beam towards the satellite allowing operation even below the equator. The status of this technology is unknown.

Figure 2.2-6 – ESA/PAA de Raysat

ALCAN is a company focused on developing a new class of low-cost intelligent antenna systems that represent a technological advance in satellite and cellular communication. The ultra-thin smart antennas, flat and capable of adjusting their beam electronically without moving parts will allow simple mounting on different platforms (cars, trains, airplanes, ships, etc.) to track all satellites (GEO, MEO & LEO), as well as such as 5G cellular networks. ALCAN has a revolutionary low-cost antenna, ultra-thin, light, flat and without mechanical moving parts, allowing it to be mounted on flat or curved surfaces. The antenna has electronic pointing capability.
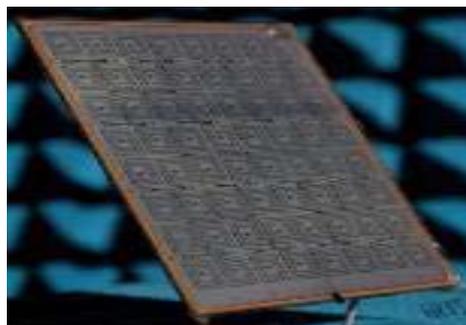
Figure 2.2-7 – ALCAN Smart Antenna

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CambrigdeConsultant has developed an antenna with three square meters and deliver quite extraordinary mobile broadband speeds – beaming high performance 5G over vast geographies and to exceptionally targeted areas from an altitude of 20,000 metres. It will be light enough to be carried by a HAPS weighing no more than a medium-sized van. It proudly sits at the heart of SPL's revolutionary high-altitude platform (HAP) and communication system.

Making the antenna weight light and super thin, whilst maintaining performance, was critical to enable an aircraft weighing just 3.5 tonnes to endure flight for over a week at a time. Weighing in at just 120kg, the full-scale antenna will enable SPL's aircrafts to easily create lift in the exceptionally thin air of the stratosphere where the atmosphere is just 10% of that at sea level.
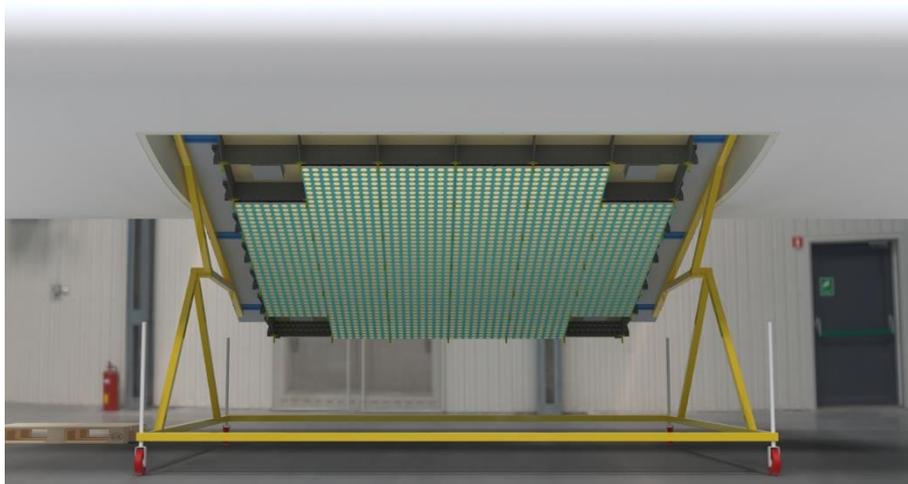
Figure 2.2-8 – CambrigdeConsultant antenna 5G for stratosphere use

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2.3. Antenna Aperture Concept Approach

The scope of this section is aimed at exposing the different technical aspects that the project will address and cover all aspects related to the design of the demonstrator and testing of the terminal. To mitigate project risk, solutions will be presented based on the experience of the personnel involved. The objective of the project is to design a prototype of a purely electronic satellite automatic pointing satellite communications terminal (SOTM). Below a block diagram with the equipment that is part of the system can be seen.
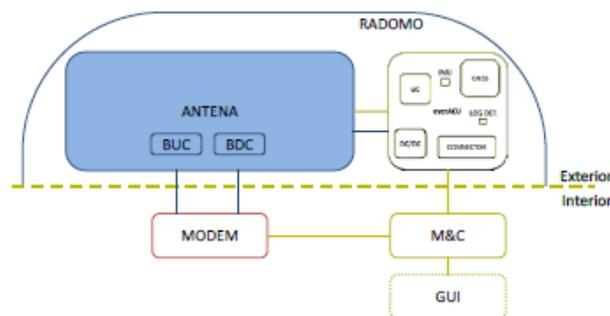
Figure 2.3-1 – Antenna System Block Diagram

- Lens antenna: Responsible for transmitting and receiving the satellite signal. The pointing direction is controlled electronically, changing the phase of each of the phasors that make up the antenna panel.
- BUC: COTS element, responsible for raising the RF signal from the Modem to Ka Band in frequency in L Band.
- BDC: COTS element, it is responsible for lowering the frequency to L Band and adapting the signal captured by the antenna to Ka Band to be transmitted to the modem.
- ACU: Responsible for calculating the pointing direction of the antenna thanks to internal sensors that continuously monitor the attitude (IMU) and position (GNSS) of the platform where it is embarked. In addition, it has a beacon signal detector from the satellite that provides information about the received signal power. It is also responsible for monitoring the status of all equipment and its alarms.
- M&C: It is responsible for monitoring all the equipment parameters and alarms and allows the configuration of the antenna parameters by the user through the graphical interface (GUI).
- GUI: User interface to facilitate control and monitoring of the status of the antenna and all the subsystems that are part of the terminal.
- Modem: commercial element, responsible for modulating and demodulating the signal to adapt the signal from Base Band to L Band and vice versa and be able to be transmitted to the antenna.
- Each of the equipment that makes up the terminal is described below, paying special attention to the development of the antenna, a critical element within the system that has a direct impact on the specifications of the terminal and the main object of the development.

The objective is to use lens technology, whose physical principles have been known for a long time, and apply it to the design of an antenna that allows maintaining the advantages of the described models (electronic pointing, multibeam,…) and eliminates some of their disadvantages (cost manufacturing and

calibration, improves elevation angles,…). The emphasis is given on wide angular coverage in order to offer a superior operability with future MEO and LEO satellite constellations as well as with GEO.

Below are the main target features:

Characteristic	Value
G/T	>13 dB / K
Frequency Rx	20 – 21 GHz Ka Band – (500 MHz instantaneous bandwidth)
Frequency Tx	29.5 – 30.0 GHz Ka Band – (200 MHz instantaneous bandwidth)
Scanning range in elevation	5–90°
Polarization	Simultaneous RHCP/LHCP Circular
Regulatory accomplishment	High isolation from adjacent satellite interference (ASI)

Table 2.3-1 Target Terminal Characteristics

The basic objective of the project is to use lens technology, whose physical principles have been known for a long time, and apply it to the design of an antenna that allows keeping the advantages of the described models (electronic pointing, multibeam,…) while suppressing some of the its disadvantages (manufacturing and calibration cost, improved elevation angles,…).

Dielectric lens antennas are attracting renewed interest for millimeter and sub-millimeter wave applications, especially for configurations with integrated feeders, called integrated lens antennas. The concept of lens-based antennas was rejected for some time due to the complexity and manufacturing costs, but today thanks to advances in lens manufacturing processes and new materials is being renewed. Lenses today are very flexible and easy to design and manufacture, being an alternative to reflective antennas at these frequencies. The objective output of the lens can vary from a simple collimated beam (increasing feeder directivity) to more complex multi-objective specifications. The lenses can be used to modify the phase or amplitude (or both) of the primary feed radiation pattern to transform it into a predetermined output radiation pattern.
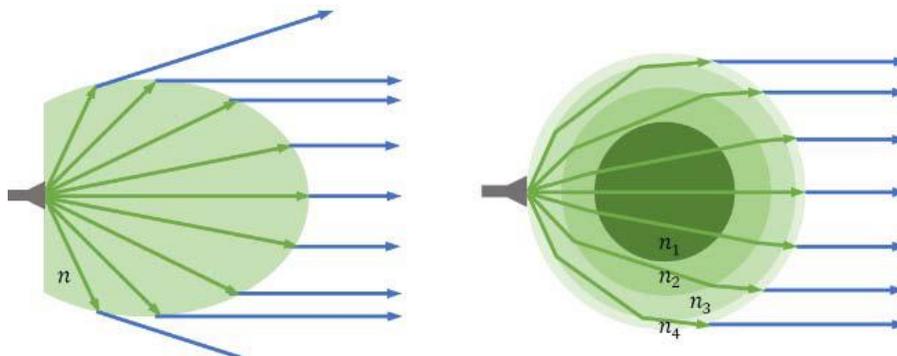

Figure 2.3-2 Antenna lens physical principles

In this sense, lenses are equivalent to reflectors. However, instead of reflection, the principle of operation of the lens is based on the refraction of electromagnetic waves on the surfaces of the lens (in

the case of isotropic homogeneous lenses), or on the dielectric material of the lens in the case of non-uniform refractive index lenses. Therefore, it is feasible to find an alternative solution to electronic planar antennas by applying spherical lens antennas in combination with electronic beam scanning antenna arrays.

The following figure presents the concept that is intended to be investigated. A spherical lens antenna will be used in combination with a conformal background array, to achieve an extended beam scanning range in combination with the activation or switching of a small number of radiating elements, which also contribute a small conical scan.
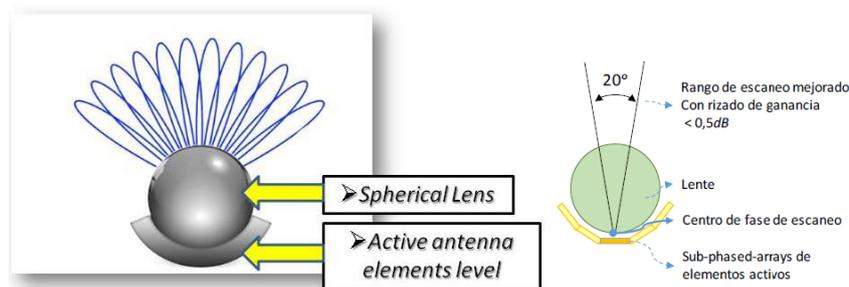
Figure 2.3-3 Lens antenna concept in combination of an active antenna array

It is intended to expand the lens concept in combination with an integrated radiating element array to create a double-curved hemispherical lens concept that represents a novel concept within the area of spherical lenses. The main objective is to reduce the profile of the future terminal using a new technique to create a double focus lens that, in addition to reducing the profile, contributes, using wave refraction, to achieving very wide coverage with the features independent of the pointing of the system, reducing the ripple in amplitude and phase of the antenna radiation pattern. Lens tracking Sub-phased-arrays of active elements 20º improve scanning range with gain ripple< 0.5dB. Satellite scanning phase center in the case of systems with classic lenses, is not possible. This fact must be a strong point in comparison with totally flat systems whose performance degrades as soon as the antenna is pointed at very low angles with respect to the horizon.
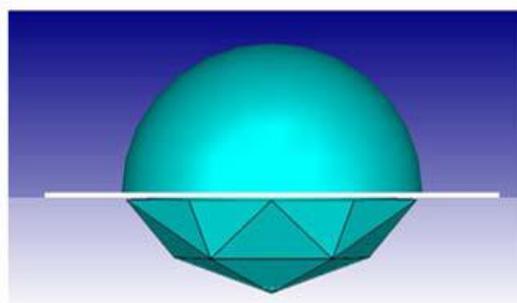
Figure 2.3-4 Conceptual view of complete terminal with low profile lens

It is important to highlight that, in addition to the design of components and the lens, there is the definition and design of the beamforming algorithms, which will make it possible to track the satellite to always ensure the communications link. To this end, the options for implementing digital or analogic beam forming algorithms have been assessed. This defines the technology and architecture of the sub-arrays that provide the necessary scanning capacity presented in the previous figure. The appropriate architecture for the application under study, of the sub-arrays that feed the lens and ensure the correct level of ripple in amplitude and phase, must be modular and with integrated control and calibration .

sub-systems. With the implementation of electronic tracking with active elements, the effective isotropic radiated power (EIRP) depends on the number of elements of each square sub-array, the gain of the radiating element and the gain of the lens, boosting in this case, its range and allowing the use of low power amplifiers. The latter reduces the requirements for thermal control and dissipated power management. Switching of the sub-arrays involves the use of pre-amplification stages to guarantee an appropriate level of SNR degradation in reception and power in transmission. The following table summarizes the concept of the spherical lens integrated with active elements, in comparison with a purely flat solution.

Advantages	Disadvantages
• Total number of radiating elements reduced. • Significantly lower number of radiating elements used in beam shaping. • Excellent suppression of side and grid lobes. It is not necessary to apply any specific amplitude distribution which simplifies the overall terminal architecture. • Very wide beam scanning angular range (up to 70 degrees) with very small scanning losses. • Global coverage and the equator problem solved. • Total cost significantly reduced. • Suitable materials available • Main beam scanning is performed by switching a number of radiating elements in combination with a small conical scanning. • Concept allows for simple multi-beam implementation. • With the implementation of electronic monitoring with active elements, smaller power amplifiers can be implemented, and the complexity and weight of the thermal control sub-system is reduced.	• A portion of the lens is outside the fuselage or platform surface, slightly increasing the profile. • The use of a smaller number of elements in the implementation of the architecture implies the use of a higher power amplifier for the unitary radiating element or the transmission system must be designed as a PESA (passive electronic scanning antenna) over the size of power to compensate for phase shift losses that occur after the amplifier stages and commutation network losses.

Table 2.3-2 Summary Advantages and Disadvantages of the solution to be explored

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Below, an approach to the final system pursued is graphically and conceptually shown, in different configurations/aircraft, from a UAV < 50Kg to a manned aircraft.
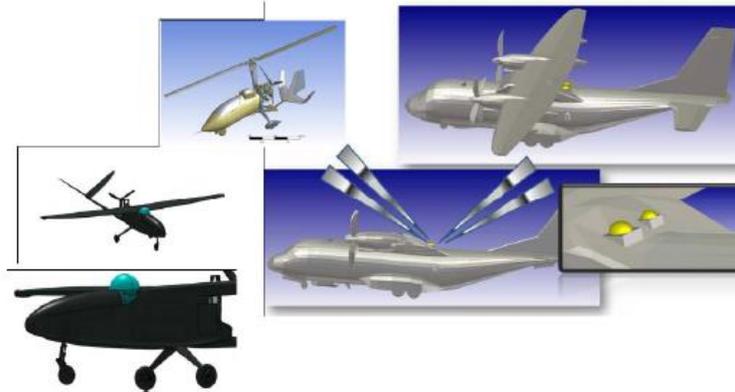
Figure 2.3–5 Various conceptual possibilities of the final system sought

State of the art of potential competitors and rationales imply that besides absolutely dominated flat antenna approach it is necessary to explore alternative ways and find a compromise solution between wind drag reductions and to boost coverage as well as instantaneous bandwidth.

Antenna Concept	General Remark and Rationale regarding project objectives
Fully Flat Antenna	Poor radiation properties towards very low elevation angles makes this option less recommendable for further implementation
Multi-faceted Antenna	Independently of optimized panel inclinations and its total number it is necessary to simultaneously process thousands of elements. In general this solutions is a feasible solution at expense of elevated costs on RF components and beamforming sub-system
Conformal Antenna	A proper conformal surface design can provide superior radiation properties but in general the remarks regarding multi-faceted array are valid in this case. Due to narrow conical scan, beamforming subsystem implementation should be relaxed. In general elevated cost solution.

Table 2.3–3 General Remark and Rationale regarding project objectives

2.4. Phased Array Concept Based on Use of Spherical Lens

An alternative solution to planar solutions can be found by applying spherical lens antennas in combination with electronic beam scanning antenna arrays. Examples of the concept that could be exploited are presented in the figures below. Basically, the concept employs a shaped array that works by switching a given radiating element, depending on the pointing direction.

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Figure 2.4-1 Multibeam Base Station Antenna

Figure 2.4-2 Antenna Sorbistiya

The following figure presents a generalized concept that has been investigated. A spherical lens antenna used in combination with a shaped background array. An extended beam sweep range achieved in combination with activating or changing a small number of radiating elements that also contribute a small conical sweep.
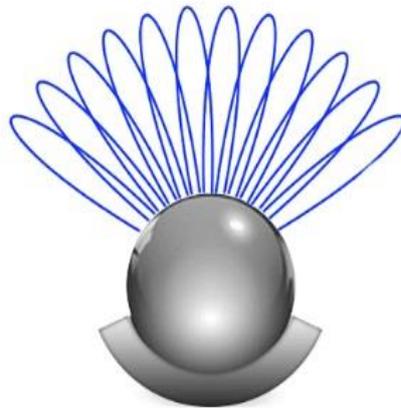
.

Figure 2.4-3 Lens antenna concept in combination of an active antenna array

The range of permittivities that are interesting for millimeter wave lens applications are roughly in the range of εr = 1.2 to εr = 11. The loss factors are conveniently better than $\tan\delta \approx 5 \times 10\text{-}3$, considering that lenses are generally large in terms of wavelength.

Very low dielectric constants are commonly used for the outer layers of multilayer lenses. Values less than εr = 1.7 are generally obtained with foam, for example polyurethane foam. Moderate values of permittivities, in the range εr = 1.7 to εr = 2.6, are required for beam-shaping lens applications.

There is a good diversity of low loss materials with these permittivities:

- ECCOSTOCK LoK (εr = 1.7, $\tan\delta < 4 \times 10\text{-}3$) [63],
- TEFLON ($\varepsilon r \approx 2.1$, $\tan\delta < 4 \times 10\text{-}4$),
- Polyethylene ($\varepsilon r \approx 2.33$, $\tan\delta < 4 \times 10\text{-}4$),
- Polypropylene $\varepsilon r \approx 2.43$),
- Rexolite (εr = 2.54), or
- Polystyrene ($\varepsilon r \approx 2.53$, $\tan\delta < 10\text{-}3$).

Higher values of permittivities are commonly used in millimeter and submillimeter substrate lenses to improve power coupling into the lens body of single-layer printed feeds. High values of permittivities are obtained, for example, from fused quartz (εr = 3.80), Kapton (εr = 3.87), MACOR ($\varepsilon r \approx 5.5$), different ceramics ($\varepsilon r$ = 6.6), Silicon (εr = 11.7), or MgO. The mechanical characteristics of all these materials are generally good for manufacturing lenses with milling technology.

A model for K/Ka band modification of this concept is to superimpose two halves of spherical lenses with different radius designed with software Catia by Edair. This structure provides additional beam deflection leading to a greater range of coverage by scanning the beam electronically. The dimensions of the lens obtained with the aim of meeting selected requirements of the future terminal.
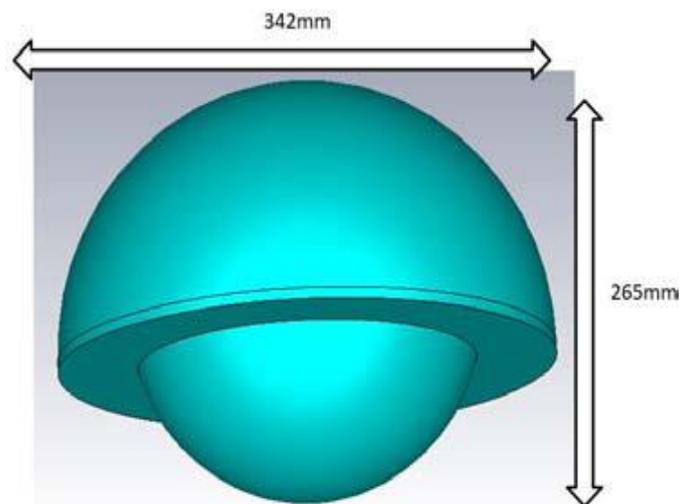
.

Figure 2.4-4 Proposed lens shape

The smaller lower lens provides a wavefront excitation for the upper larger lens with a certain phase distribution of the electric field. The result is that the main beam is tilted at elevation angles lower than the feed horn points because the focus of both lenses is slightly offset. The diagrams that will be presented below show a 2D pattern in a scanning range of up to 74 degrees.

The actual illumination of the lens will be produced by an active set of radiating elements distributed below it. The figure below shows a possible distribution of radiating elements using the form of a geodesic vault composed of identical triangles. In this way, the classic technology of flat and printed circuits can be applied.
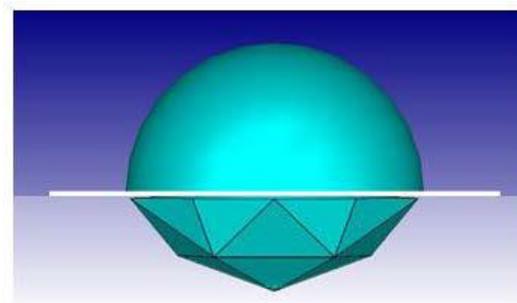
Figure 2.4-5 Un concepto del sistema completo

As a proof of concept, a simple corrugated horn antenna is used instead of an array of antennas.

- The height of the complete system 27cm
- The focus of the lower lens is displaced with respect to the focus of the upper lens
- Material used for lens Ɛr=2.7, tgδ=0.0005
- The same corrugated horn is used in computations on both bands trying to use the same aperture that should be replaced by a set of radiating elements. Two orthogonal modes are used to generate the circular polarization.
- The model used includes a metal platform around the simplified lens that must model the influence of a platform that supports the active antenna system.

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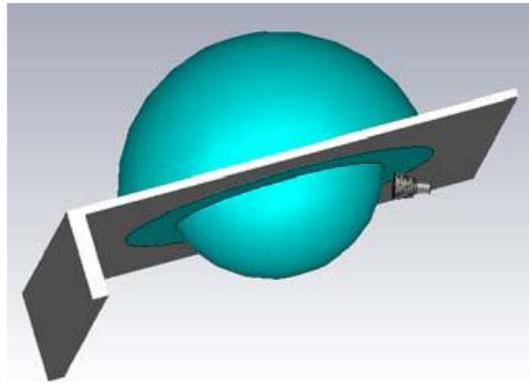
Figure 2.4-6 Lens model used in simulations
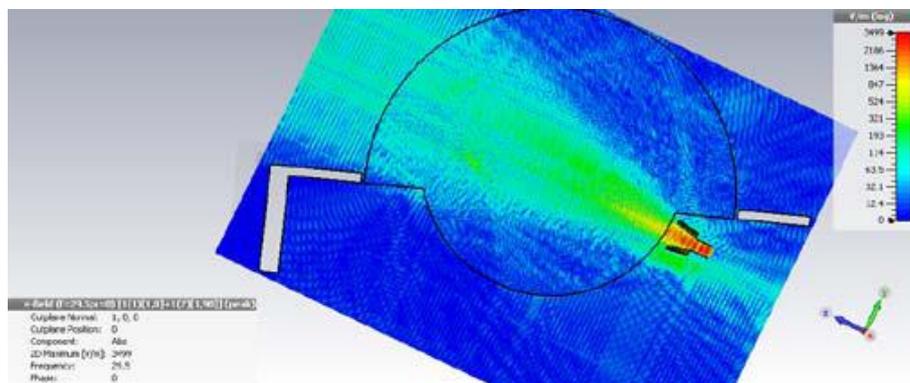
Figure 2.4-7 Example of the electric field distribution inside the Ka-band lens

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2.5. Results for the lowest aiming position

This section shows results for the lowest aiming position analysed where diagrams represent valued not normalized.

Rx receiving antenna case:

Explanatory note: The model is oriented so that the antenna points at 20 degrees to the horizontal plane. Refraction effect increases beam scanning range up to 18 degrees
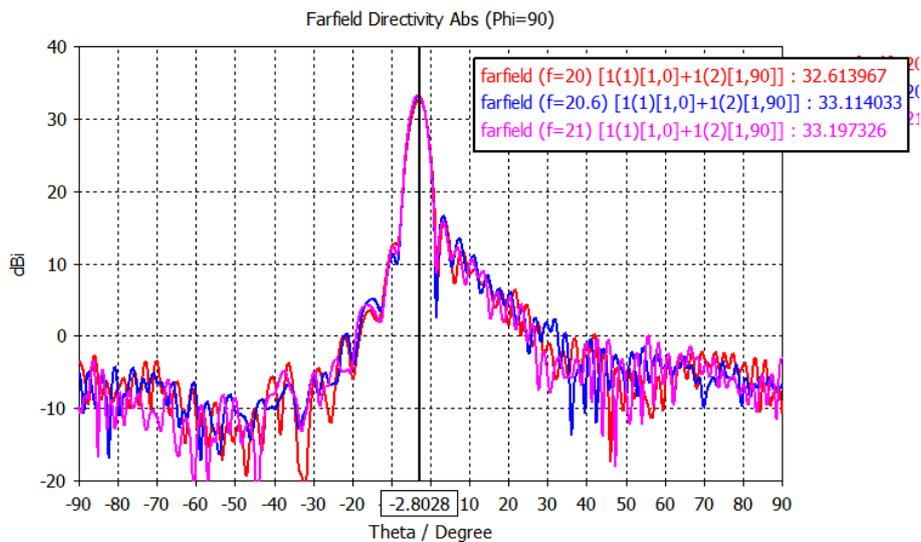
Figure 2.5-1 Radiation patterns in the elevation plane and frequencies 20GHz, 20.6GHz and 21GHz
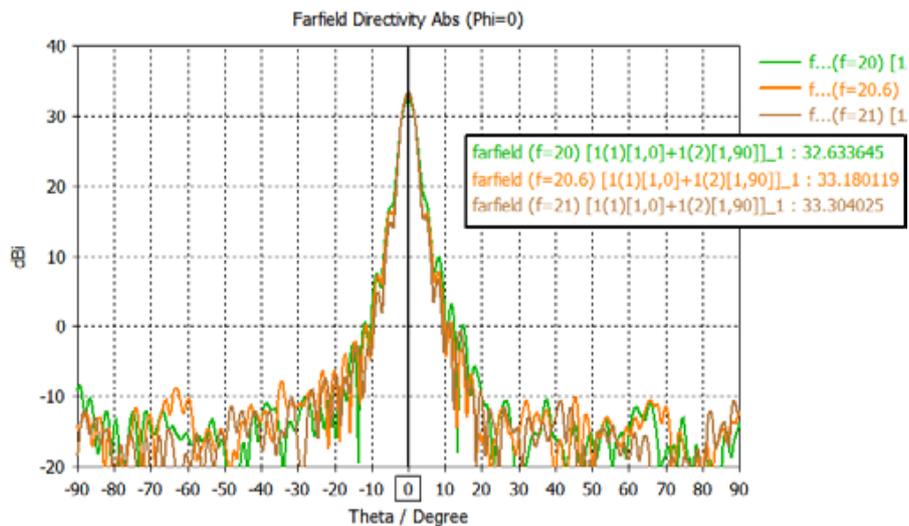
Figure 2.5-2 Radiation patterns in the azimuth plane and frequencies 20GHz, 20.6GHz and 21GHz

The following diagram shows the behaviour of the radiation pattern with respect to the skew angle of the mobile platform while the system points at the satellite. Good behaviour is shown by the lateral lobes, which in any case retain a fairly low level.

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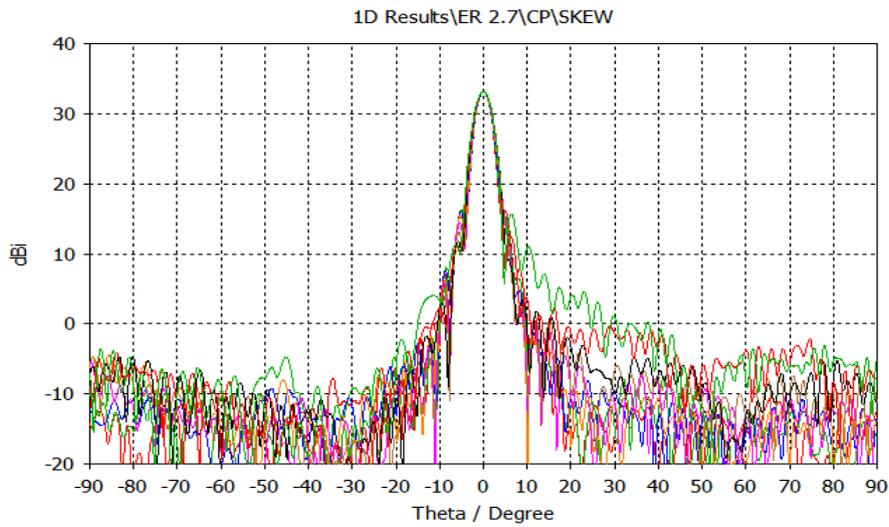
Figure 2.5–3 Example at 20.6GHz of variation of phi from 0 to 80 degrees – behavior with respect to SKEW angle

Tx transmitting antenna case:

The model is oriented so that the antenna points at 20 degrees to the horizontal plane. Refraction effect increases beam scanning range up to 17 degrees

Figure 2.5–4 Radiation patterns in the elevation plane at frequencies 29.5GHz, 29.75GHz and 30GHz
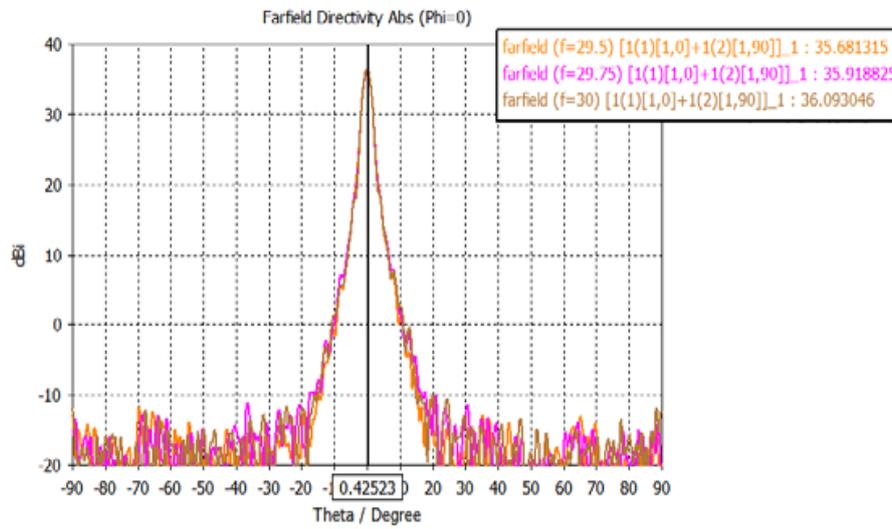
Figure 2.5–5 Radiation patterns in the azimuth plane and frequencies 29.5GHz, 29.75GHz and 30GHz
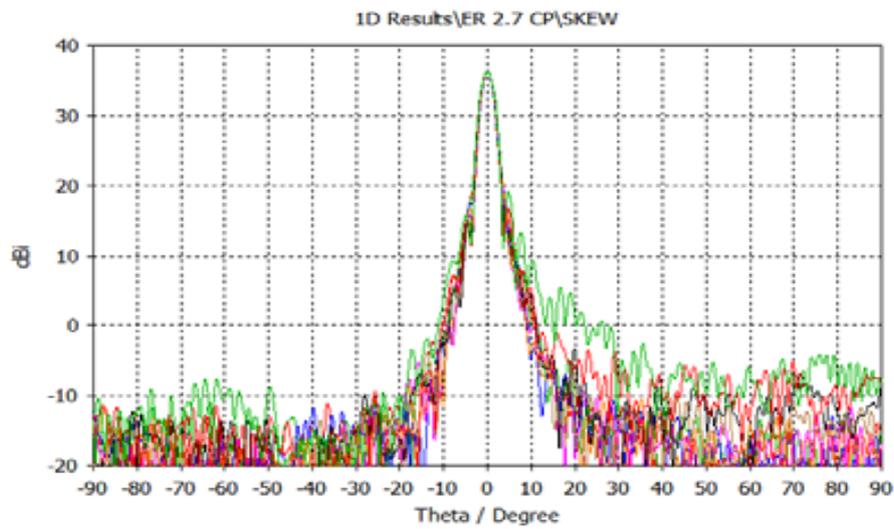
Figure 2.5–6 Example at 29.75GHz of variation of phi from 0 to 80 degrees – behavior with respect to SKEW angle

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2.6. Results for the position towards 45 degrees with respect to the horizontal plane

Rx receiving antenna case:

The model is oriented so that the antenna points at 45 degrees to the horizontal plane. The refraction effect results in the antenna pointing 3.5 degrees lower to 41.5 degrees.
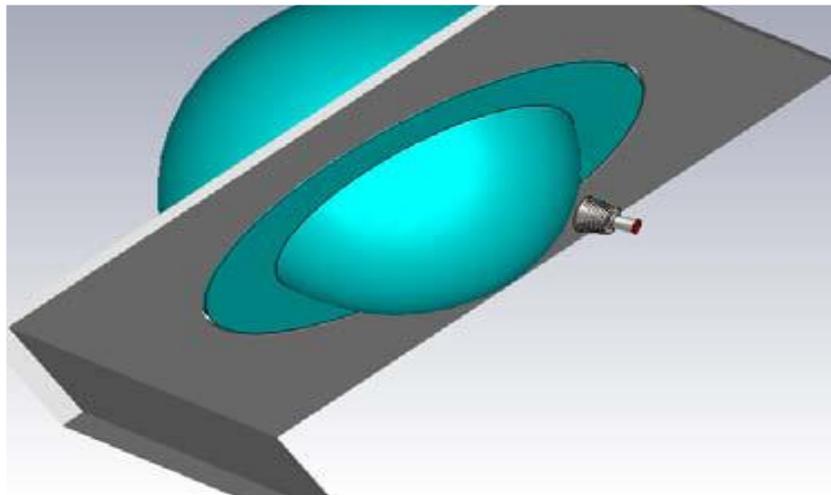
Figure 2.6–1 Lens model rotated 45 degrees used in simulations
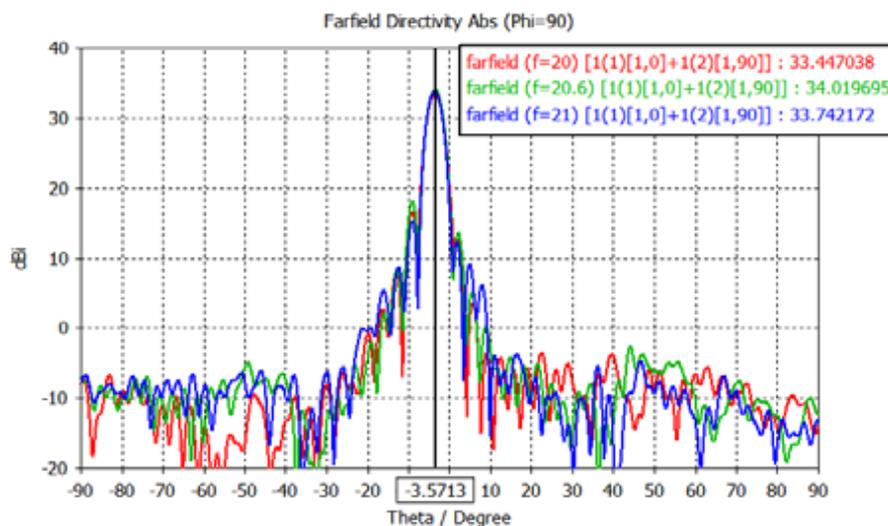
Figure 2.6–2 The radiation patterns in the elevation plane and frequencies of 20GHz, 20.6GHz and 21GHz and pointing at 41.5 degrees with respect to the horizontal plane

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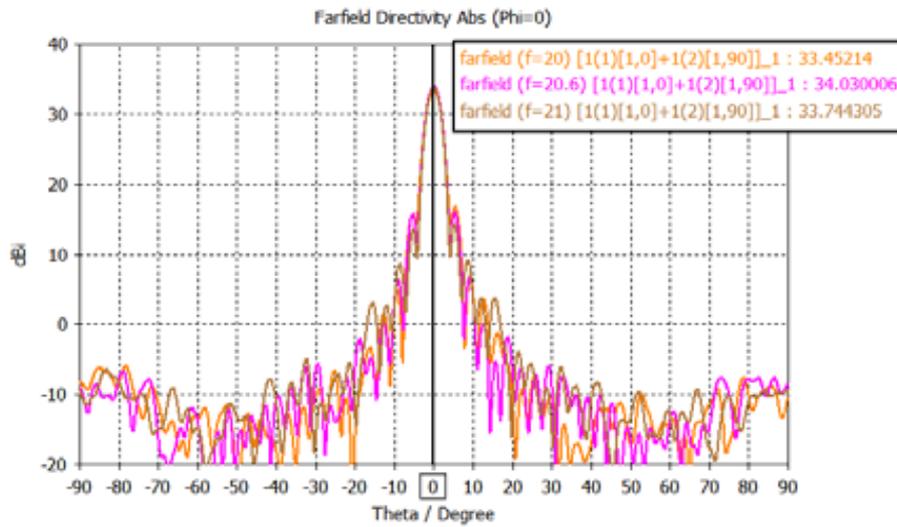
Figure 2.6–3 The radiation patterns in the azimuth plane and frequencies of 20GHz, 20.6GHz and 21GHz and pointing at 41.5 degrees with respect to the horizontal plane

Tx transmitting antenna case:

The model is oriented so that the antenna points at 45 degrees to the horizontal plane. The refraction effect results in the antenna pointing 3.5 degrees lower to 41.5 degrees.
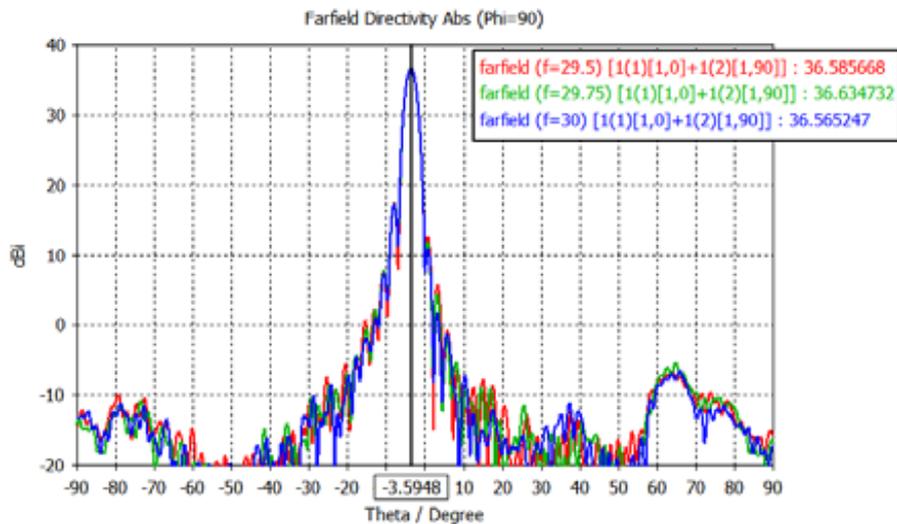
Figure 2.6–4 The radiation patterns in the elevation plane and frequencies of 29.5GHz, 29.75Hz and 30GHz and pointing at 41.5 degrees with respect to the horizontal plane

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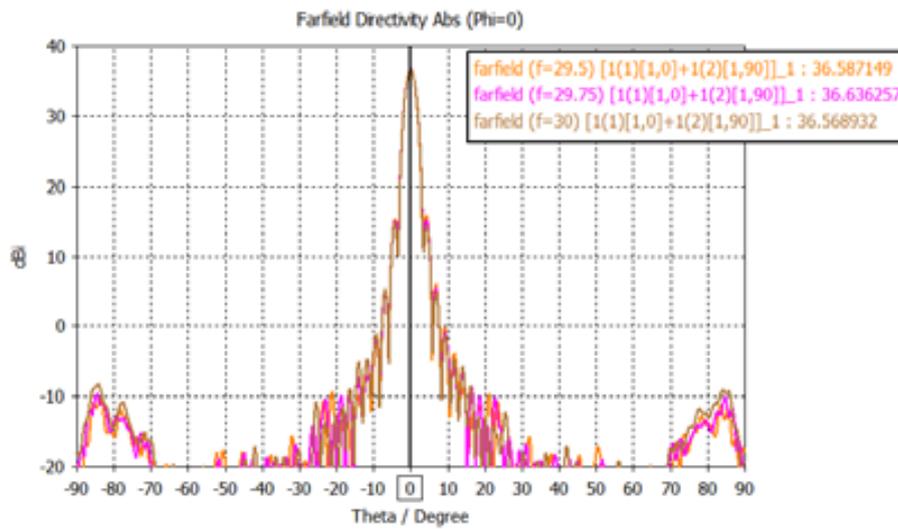
Figure 2.6–5 The radiation patterns in the azimuth plane and frequencies of 29.5GHz, 29.75Hz and 30GHz and pointing at 41.5 degrees with respect to the horizontal plane

2.7. Results for the position towards 90 degrees with respect to the horizontal plane

Rx receiving antenna case:

The model is oriented so that the antenna points at 90 degrees to the horizontal plane.
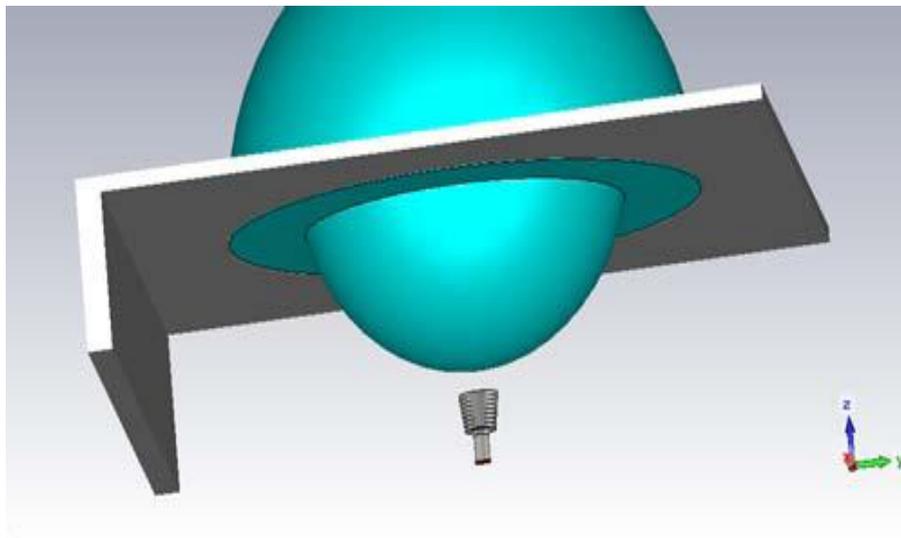
Figure 2.7–1 Lens model rotated 90 degrees used in simulations.

Rx case:

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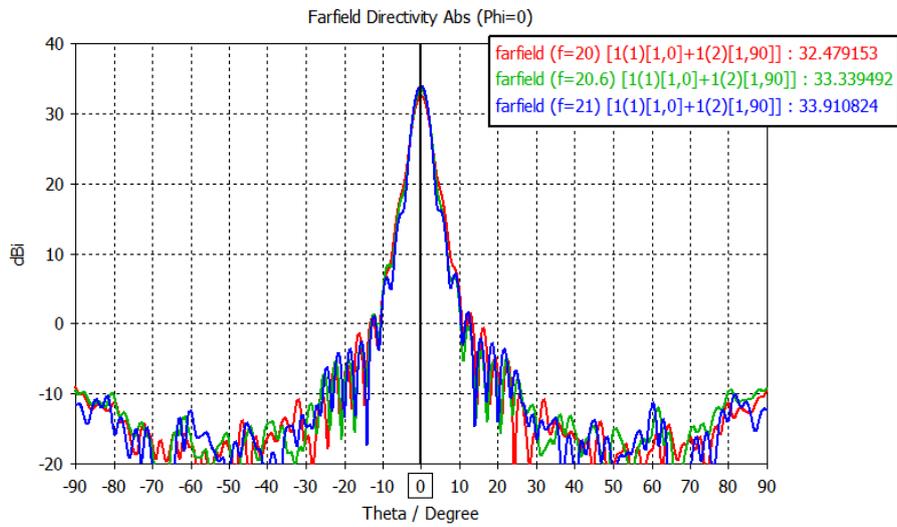
Figure 2.7-2 Radiation patterns in the phi=0 plane and frequencies of 20GHz, 20.6.GHz and 21GHz
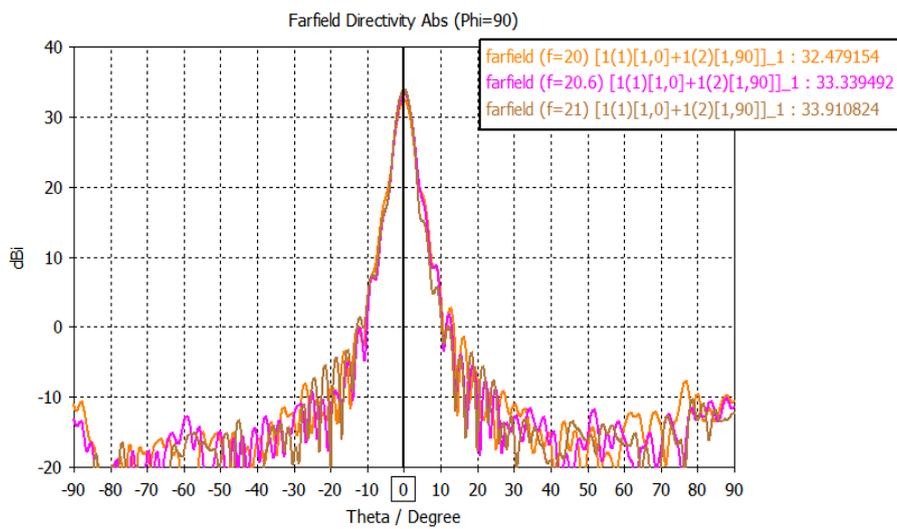
Figure 2.7-3 Radiation patterns in the phi=90 plane and frequencies of 20GHz, 20.6.GHz and 21GHz
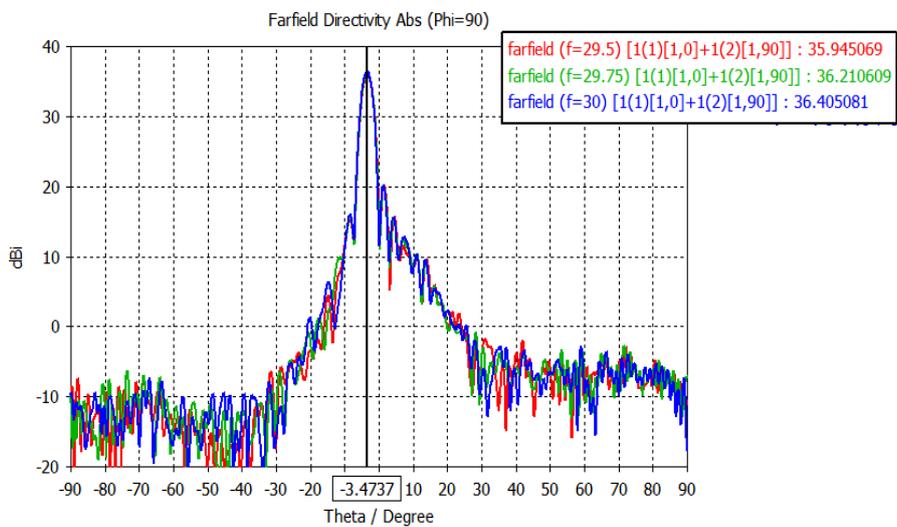
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Tx transmitting antenna case:
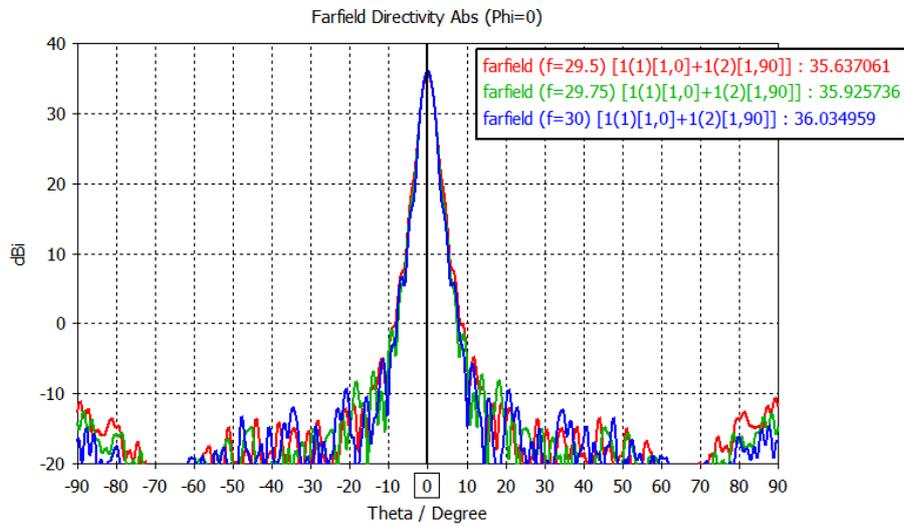
Figure 2.7–4 Radiation patterns in the phi=0 plane and frequencies of 29.5GHz, 29.75GHz and 30GHz
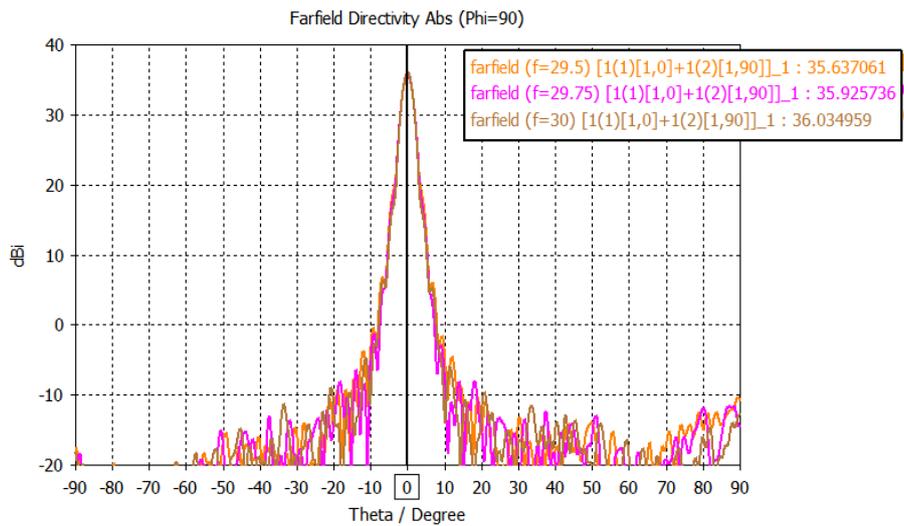
Figure 2.7–5 Radiation patterns in the phi=90 plane and frequencies of 29.5GHz, 29.75GHz and 30GHz

2.8. Summary of properties with respect to coverage

Using the 3D patterns, a summary of the properties with respect to achieving a very wide beam scanning range can be made.

This document concerns communications from High Altitude Platforms (HAPs), which may be based on either aircraft or balloons, and stationed in the stratosphere at altitudes of around 17–22 km. This geometry will allow for line-of-sight links which are required for effective exploitation of the high bandwidths available at mm-wave frequencies. Multi-cell architectures will allow for spectrum re-use and will require a multi-beam HAPS payload possibly using a group of spot-beam antennas. The level of carrier-to-interference ratio (CIR) is a consequence of the spatial overlap of the antenna radiation patterns.

The ITU has allocated the 47/48 GHz band for usage by HAPs worldwide, and the 27/31 GHz band has also been allocated to about 40 countries. At these frequencies, it is difficult and expensive to produce electronically re-configurable antennas based on phased-array principles and digital beam forming (DBF). For example, DBF presents challenges associated with the close spacing of radiating elements, the requirement for a large number of elements, the need to minimise sidelobe levels, the cost and complexity of RF active circuits, or the problem of scanning losses. The last point is particularly detrimental for HAPs communications because links to users at low elevation angles, where scanning loss for a horizontal planar array are worst, experience also the longest free space and atmospheric losses. Nevertheless, several programmes are developing DBF antennas for Ka band which reports on a 16-element module, and the Japanese HAPs programme has reported a similar prototype for 28 GHz while admitting that horn antennas stabilised by mechanical gimbals are a more pragmatic solution for 48 GHz.

The most conservative solution for the HAP antenna payload is a group of aperture antennas, where each antenna serves a single quasi-stationary cell. This approach has been studied in some depth where the important relationship between the radiation patterns and the CIR levels on the ground has been quantified for various channel re-use schemes. Ultimately, the economic viability of a HAP cellular network may be determined by the extent to which it can maximise the re-use of spectrum. This document explores the properties of multi-beam antennas based on spherical lenses, since these can yield a much more compact HAP antenna payload compared to the use of single-beam aperture antennas.

Case of antenna working in reception

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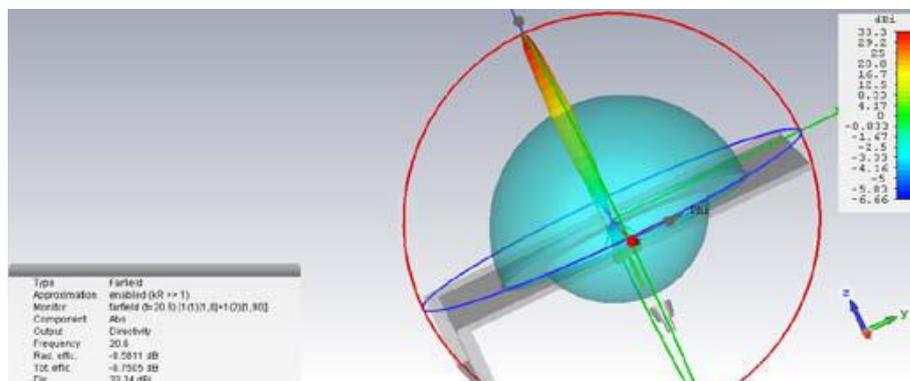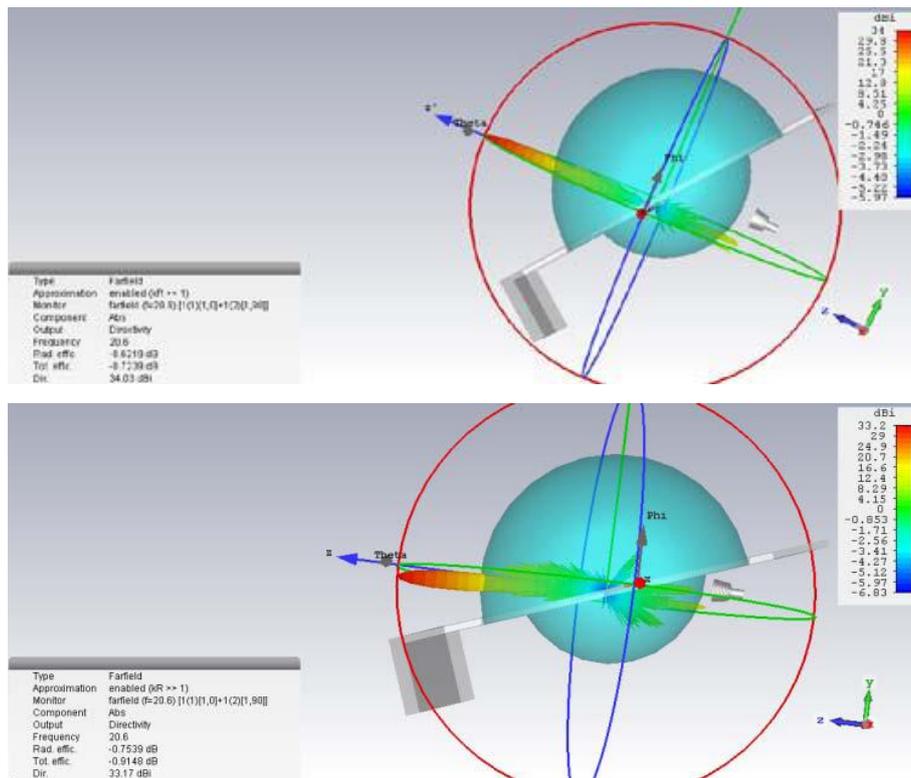
Figure 2.8–1 Angular coverage in case of reception in 20.6GHz example

Antenna case working in transmission

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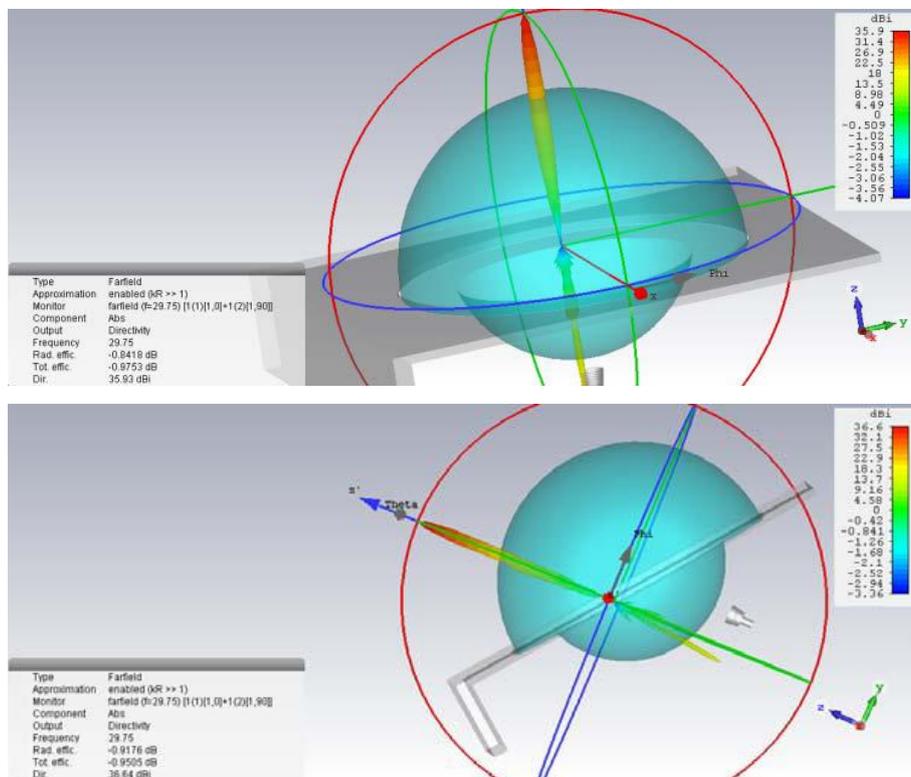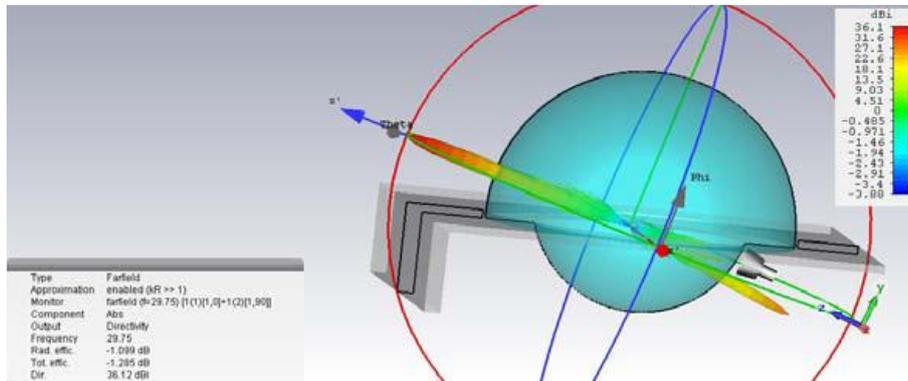
Figure 2.8-2 Angular coverage in case of transmission in 29.75GHz example

It is worth listing the pros and cons of using dedicated beams, i.e. one antenna per cell. Advantages include:

- each antenna pattern can be tailored to the shape required by each cell.
- asymmetric beams yield equal size, circular cells, which aids tessellation of cells and maximises coverage
- low sidelobe levels are feasible e.g. -40 dB relative to peak gain.

Disadvantages include:

- A bulky, massive payload, which requires mechanical stabilisation.
- A non-reconfigurable network.

These disadvantages can to some extent be overcome with multiple-beam antennas which allow for the payload mass and volume to be reduced, but at the expense of eroding the advantages associated with dedicated beams because it becomes more difficult to tailor each beam to each cell. Multi-beam aperture antennas typically use a cluster of primary feeds to illuminate a secondary aperture which might be a prime-focus reflector or lens, but the angular range of scanning is limited. For a HAP payload a wide conical scan is needed e.g. 150° for users at elevation angles as low as 15°. The following sections explore the potential to use multiple-beam, wide-scanning antennas based on spherical lenses, and quantify the CIR values which could be expected.

In the context of HAPs communications, the very useful property of antennas using spherical lenses is their ability to form multiple beams over a wide range of angles without inducing any scanning loss. A number of spherical lens variants are well know, and some are briefly reviewed below.

A classic type of spherical lens is the Luneburg lens, which focuses an incident plane wave at a point on the lens surface. The spherical geometry allows for multiple beams to be produced from multiple feeds and it is this property which is attractive for a HAP payload. The Luneburg lens requires a radial variation of dielectric constant (εr). Thus the dielectric constant varies from 1 at the lens edge to 2 at the centre and there is no reflection loss due to abrupt transitions. This leads to a very good aperture efficiency, but it somewhat problematic to manufacture. In practice such a lens is often fabricated from a set of concentric shells and this inevitably degrades the efficiency. However, for limited bandwidth applications a two-shell design can give almost equivalent performance.

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A single shell spherical lens has no single focus, but exhibits a paraxial focus when a small proportion of the lens is illuminated. The paraxial focus may lie inside or outside the lens outer radius. A low dielectric spherical lens can give good performance, Teflon lens (εr = 2.08) for wide–scanning automotive radar at 77 GHz and is, of course, much more simple to manufacture than a multi–shell lens.

Using the Luneburg lens aperture distribution, where the primary feed pattern is also taken into account, the far field radiation pattern can be computed. The geometry is illustrated in next figure for a generalised lens where the focus may lie inside or outside the lens radius a. However, for the remainder of the analysis we will assume a conventional Luneburg lens where f = a.
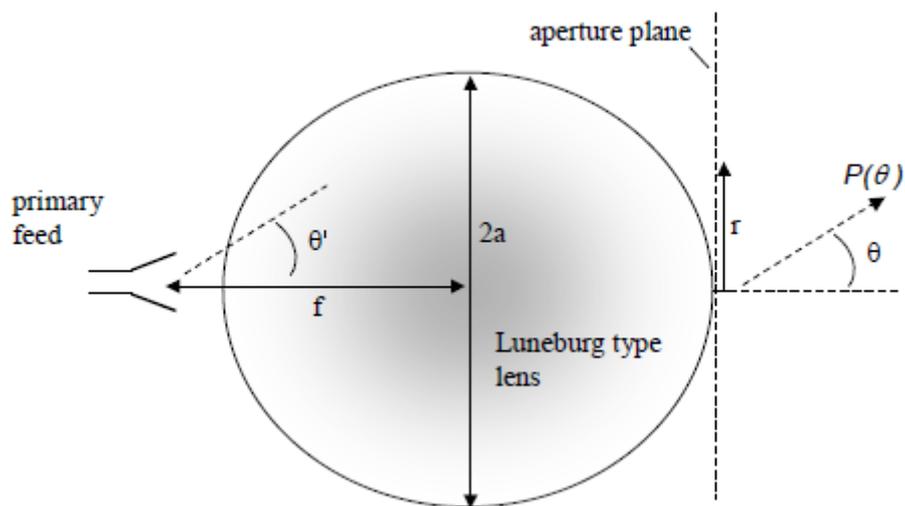
Figure 2.8–3 Morgan's geometry for generalised Luneburg lens showing aperture plane
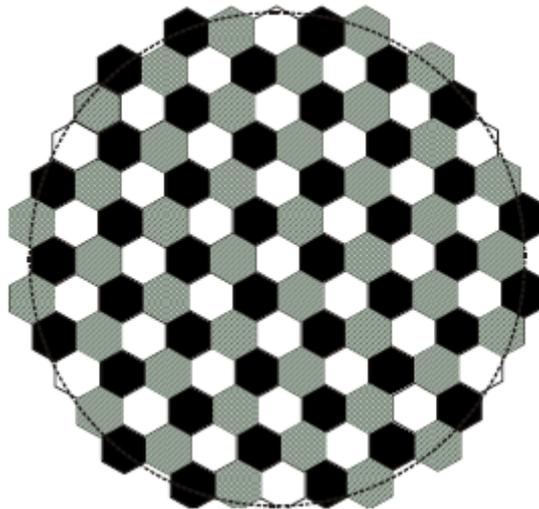
Figure 2.8–4 Layout for 121 cells using 3 channels.

POWER CONTOURS AND CO–CHANNEL INTERFERENCE.

In contrast to earlier studies where each antenna beam is optimised, the use of multiple–beam spherical lens antennas leads to each beam of a given cluster having the same beamwidth and also having

circular symmetry. Taking the layout of 121 cells shown in previous figure, where cells are arranged in 6 concentric hexagonal rings, we can specify an antenna beamwidth associated with each ring based on the mean required beamwidth. This is a modification of the usual methodology and leads to non–circular cellular power footprints but allows the use of a single spherical lens aperture for each ring and thus a much more compact antenna payload. Elements of such a payload are illustrated in next figure, which shows how the innermost group of cells are served by the smallest spherical lens with a cluster of appropriately spaced feeds, and the outermost group of lenses are similarly served by the largest spherical lens. The indicated lens diameters are approximations based on uniform aperture illumination at carrier frequency of 28 GHz and thus serve as a benchmark estimate for minimum antenna dimensions at this frequency.
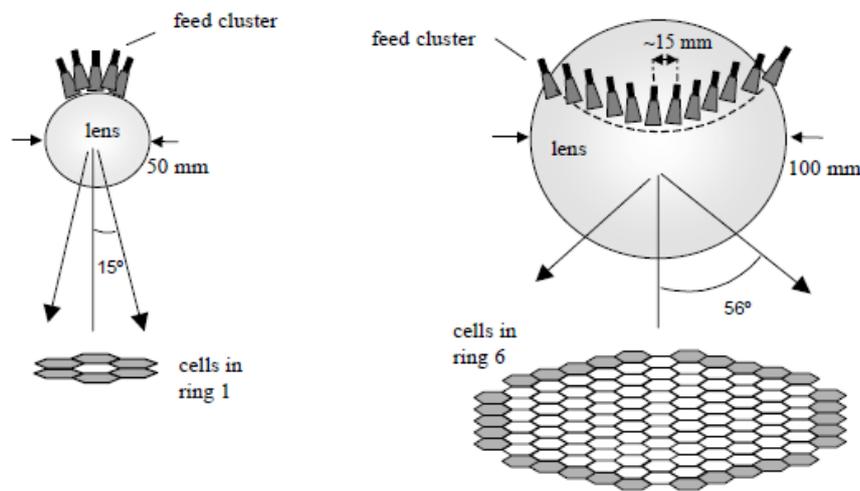
Figure 2.8–5 Concept for antenna payload: multi–beam Luneburg lens for each cell group

To close the analysis we present an estimate of the total mass for the HAP antenna payloads which have been discussed. For the dedicated beam payload, a working estimate for total lens mass can be derived as follows: Using the mass of our experimental asymmetric beam lens antenna as a benchmark, and noting that, to a good approximation, there are straightforward relationships between HPBW, mass, and lens diameter D.

The estimate for the mass of the multi–beam spherical lens payload can be derived from the diameter of each lens and (assuming a single shell lens design) the material specific gravity. Again assuming a polyethylene material, whose density is 947 kg/m3, and uniformly illuminated apertures for the minimum size payload case, a mass of 1.93 kg is derived for the group of 6 spherical lenses. The figure would be reduced for multi–shell or Luneburg type lenses. Again, the mass of the primary feeds has not been considered, as it is possible that these could be very similar for the two payload cases and their number would also be the same.

A comparison of the dedicated beam payload, assuming –40 dB sidelobe floors, and multi–beam spherical lenses are summarised in next Table. The CIR levels offered by the dedicated beam payload may, to a good approximation, be replicated by using the spherical lens payload with 60° beamwidth primary feeds. It is stressed that the mass of the elements presented based on extrapolation from those of representative components.

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	number of primary feeds	number of lenses	estimate of total lens mass (kg) (for 28 GHz)	CIR (dB) (minimum / maximum)
dedicated beams	121	121	28.8	12 / 24
multi-beam spherical lenses: (i) minimum aperture size	121	6	1.93	6 / 18
(ii) scaled aperture with 60° primary feeds	121	6	3.50	12 / 29

Table 2.8–1 Comparison of payload properties and CIR values for dedicated beams and multi–beam

2.9. Advantages and Disadvantages

Advantages:

- Lower number of active elements
- Beam is formed using only few active elements
- Excellent side lobe suppression (no grating lobes)
- Great scan area with lower gain losses (+/– 60,70) degrees
- Significantly lower cost solution in comparison with classical approach
- Use of proven dielectric material for lens fabrication
- Scan is performed by elements switching or/and employing a small main beam scan

Disadvantage:

- A part of lens outside of the fuselage increasing antenna profile

3. Uses Cases and Coverage Areas

3.1. Global data of the telecommunications and audiovisual sector

The penetration of all final services increased, with the exception of fixed telephony broadband penetration in mobility increased 3.4%, to 107.5 subscriptions per 100 inhabitants, and that of fixed broadband reached 35.3 lines for every 100 inhabitants.

Quad and quintuple packages as a whole decreased in 2021. Package types that combine fixed and mobile voice and band services broadband (and they add pay television in fivefold) fell this year by more than 150 thousand units. On the contrary, the package that includes three services stands out: broadband fixed, mobile voice and mobile broadband, grew by almost half a million units until 1.3 million by the end of 2021. The average spending of households with a quadruple package decreased considerably by the end of 2021, households with a quadruple package (fixed and mobile voice services and fixed and mobile broadband) spent 47.9 euros per month on average, 5.6% less than at the end of 2020. On the other hand, households with a quintuple package spent 77.1 euros per month, 1.8% more than in 2020.Investment in the sector exceeded 7.5 billion the total investment in the sector amounted
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to 7,574 million euros. If you do not include the spectrum acquisitions, investment in the telecommunications and audiovisual sector in 2021 it was 29% higher than in 2020. Progress in the deployment of next generation access networks (NGA) the total number of NGA accesses (new generation networks) deployed at the end of the year reached almost 78 million installed accesses, of which 68.5 million were fiber and 9.4 million HFC DOCSIS 3.x. These figures represented 9 million FTTH new accesses compared to the previous year. Wide coverage of mobile services with 4G technology and significant deployment of 5G networks in their first year of service. The equipment that provided coverage with 4G technology grew by 5.5%, reaching a total of 59,359 base stations and a population coverage of 99.6%. Likewise, in the year 2021, up to four mobile operators were already commercializing massive mobile internet services through the fifth generation with the standard of mobile communications (5G). In December of that year there were already active of 9,380 equipment that provided communications with 5G technology with coverage over the population of 82.3%.

3.2. Fixed communications

FIXED TELEPHONE

The fixed line fleet registered a drop of 0.9% over the total number of fixed lines resulting in a net decrease of 395 thousand lines to 19 million. It fell nine tenths to 40.2 lines per 100 inhabitants. The number of fixed lines packaged with other fixed services remains stable and mobile 78% of total fixed lines were bundled at the end of 2021, a value similar to the previous year. 65.7% of the total were included in a quadruple package or fivefold, compared to 65.1% in 2020.

The market share for fixed lines of the three main operators reached 82.6%, in comparison with 85.3% in 2020, Movistar lost nine tenths in the year to 42.7% of the lines. If we add the MASMOVIL Group (with the inclusion of Euskaltel), the share of the four reaches 96.3%.

FIXED BROADBAND

Broadband connections reached 16.7 million lines active broadband accesses on fixed networks increased 3.2% in the last year, up to 16.7 million. This volume of lines reached a rate of 35.3 lines per every 100 inhabitants. · Active FTTH lines exceeded 79% of total broadband xDSL technology continued to decline. In 2021, these lines decreased by 30.6%, while FTTH connections increased by 11.4% to reach 13.2 million, a figure that represents 79% of total broadband accesses. 14.86 million lines with connection speed of 100 Mbps or higher

The improvement in access networks was reflected in an increase in line speeds contracted broadband. 90.5% of the lines had a speed equal to or greater at 30 Mbps, compared to 86.8% in the previous year. The percentage of lines with speed of 100 Mbps or higher reached 89% compared to 84% in 2020. Likewise, accesses with speeds of 500 Mbps or higher totaled 7.2 million (43.4% of total accesses broadband). The MÁSMOVIL Group was the operator with the largest increase in band lines fixed width 522 thousand new broadband lines were added to the market. MASMOVIL Group added 357 thousand accesses in 2021. Movistar ended last year with a loss of 82 thousand lines and a share of 34.7%; Vodafone lost just over 147 thousand lines and the park of Orange added 6 thousand new accesses.

Broadband access traffic reached almost 54 million Terabytes. A total traffic of 54 million Terabytes was recorded, 16.7% more than in 2020. The increase in average monthly traffic per line increased by 13% to 269 Gigabytes.

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NEBA Local was the whole sale service with the highest demand for access. The virtual access service to the fiber network (NEBA Local) closed the year with a total of two million accesses, a figure that represents an increase of 19.4% in the last year. Demand for Telefónica's wholesale indirect band Ethernet access service NEBA FTTH broadband increased slightly and closed the year with 959 thousand lines.· Wholesale FTTH access contracted to alternative operators was the wholesale service with the greatest increase. The increase in the contracting of wholesale access to operators stood out alternatives offered through own networks; these operators totaled 836 thousand new accesses until reaching 1.82 million active wholesale accesses over FTTH networks, a figure that represents an increase of 84.1% in the last year. The wholesale loop unbundling service continued to decline the loop unbundling service decreased by 250 thousand accesses, reaching 390thousand. The main alternative operators, as their FTTH network deployment progresses, They use this wholesale modality to a lesser extent to provide service to their end customers.

3.3. Mobile communications

MOBILE PHONE

The number of mobile lines increased to 56.9 million. The mobile park added 1.2 million lines, thanks to the increase in the modality of contract that, with an increase of 1.6 million lines, offset the loss of 427 thousand lines in prepaid mode. Penetration at the end of the year reached 120 lines per every 100 inhabitants. Wholesale mobile communications services recorded an increase overall income. Total revenue from the wholesale market reached 1,938.6 million euros, a figure which represented an increase of 14.3% compared to the previous year. Mobile access service to third-party operators was the one that contributed the most to this significant growth, with an increase in income related to this service of 15.8%. The service mobile access service had the highest business volume, surpassing the termination service national service, which historically, in terms of income, had been the most important.

MOBILE BANDWIDTH

Mobile broadband services maintained their growth rate in 2021. In 2020, a total of 50.9 million mobile lines accessed the Internet through the mobile communications networks (2G, 3G, 4G and 5G). This figure represented 1.7million more lines than in 2020. The majority of these lines, 49.4 million, they are connected to the Internet through their mobile phone.

Significant increase in the consumption of mobile broadband services. In 2021, data traffic managed through mobile networks grew by 43.1% compared to from the previous year, reaching 4.3 million Terabytes. For its part, the increase in average monthly traffic per line increased by 38.3% to 7.1 Gigabytes. 4G networks represented 89.2% of the total recorded traffic.

Growth of 5G technology in the mobile broadband market. Although the mobile internet access service with 5G networks began properly in the last quarter of 2019, it was in 2021 when this technology was consolidated through the wide range of rates that allowed connection to the 5G network of the main market operators. However, traffic recorded on 5G networks was still reduced compared to the rest of the technologies, of only 22,790 terabytes.

Audiovisual services, recovery of advertising revenues, and advertising revenues in the audiovisual services market grew by 9% to the 1,974.5 million euros. This figure shows a recovery with respect to the decrease experienced in 2020 (COVID-19 confinement period) but without reach the 2019 values.

The number of subscribers to paid audiovisual services slightly decreases "traditional". In line with previous years, the progressive increase in subscribers continued in 2021 to paid audiovisual services. However, in 2021, for the first time, a decrease in the number of subscribers to "traditional" pay television platforms.

Subscriptions to OTT audiovisual content platforms reach 18.9million subscribers. This figure includes, for the first time in the framework of this sectoral report, the subscribers/subscribers to the large payment audiovisual service platforms in Internet streaming (Amazon Prime Video, Netflix, HBO and Disney+),The data refers to the number of contracts that pay a periodic fee of subscription to the service.

Mobile network infrastructures. Base stations. In the year 2021, four telecommunications operators (Movistar, Orange, Vodafone and MÁSMOVIL Group) marketed mobile internet services through the fifth generation of the mobile communications standard (5G).

In December of that year, a total of 9,380 base stations were already active, providing 5G technology coverage based on the NSA (Non Stand Alone) standard. This technology it will allow theoretical data transmission speeds of up to 2 Gbps to be reached. In addition, this new technology will not only offer faster data transfer speeds, but that will enable communications on these platforms to have a latency range much lower than that registered in previous developed technologies. Thus, 5G with NSA standard will allow a latency of less than 10 milliseconds to be obtained, while the 4G technology, the most advanced until the implementation of 5G, reaches a latency of 200 milliseconds.

However, it is expected that, in the future, and once it is fully available after its standardization, operators will move to deploy 5G technology based on the standard SA (Stand Alone) which will be able to reach data transmission speeds of up to 20 Gbps and a latency of 1 millisecond. These two technological improvements combined with a greater capacity to connect mobile devices simultaneously are the characteristics that, in the near future, will make it possible to offer the market a whole series of new mobile services based on what has been called the internet of things (Internet of things, IoT).

For their part, operators continued to invest in other mobile technologies to expand and improve their coverage. Thus, for the seventh consecutive year, the equipment based on 4G technology or also called Long Term Evolution (LTE), they grew by 5.5%, reaching a total of 59,359 base stations. Although in one in the first phase, the operators were concentrated in the main cities, progressively has shown a widespread deployment in the rest of the territory.

Regarding the number of 3G technology base stations declared in the year 2021 — 62,946 active stations — represented a year-on-year increase of 1.7%. Likewise, mobile operators declared more than 50,000 technology base stations2G implemented throughout the territory.
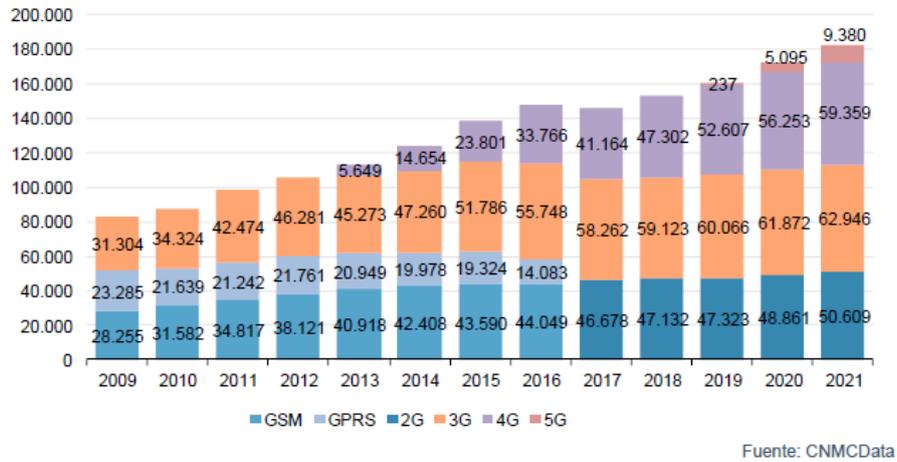
Figure 3.3-1 Evolution of the number of base stations by technology

Considering the total voice traffic, whether its origin is a fixed line or mobile, a drop of 4.6% in the last year, placing total traffic around 136 thousand millions of minutes. Although a growth in traffic was experienced in 2020 fixed origin and mobile, this year 2021 traffic from fixed origin falls by 20.2%, on a downward path compared to2019 (before the pandemic) 5G is still little deployed.
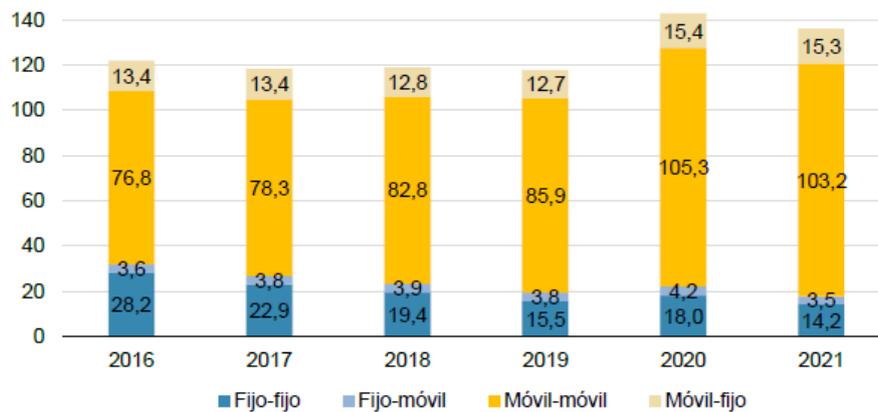
Figure 3.3-2 Evolution of voice traffic by origin and destination (billions of minutes)

The data in the following graph shows the average consumption per line, which is reduced to a lower value than in 2019, with a decrease of 18.5% compared to the previous year. The biggest fall significant occurs in the residential segment with a decrease of 26.8% each user makes calls for 928 minutes/year.

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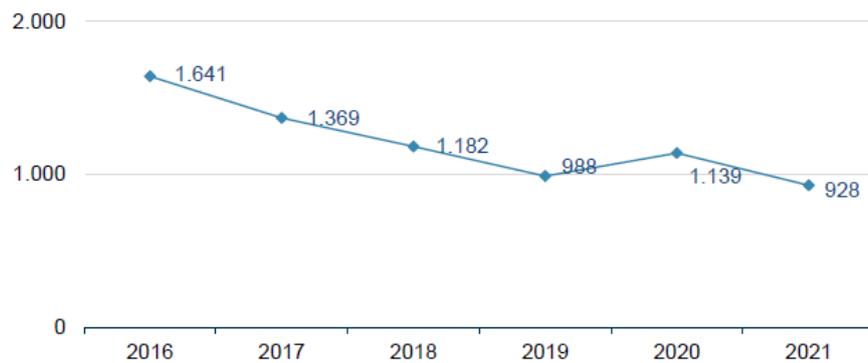
Fuente CNMCData

Figure 3.3-3 Minutes per fixed line and year (minutes/line)

The traffic improvement of broadband access networks through the deployment of NGA accesses, as well as the marketing of offers with higher connection speeds, has led to a continuous increase in data traffic in recent years. It should be noted that in Spain some operators marketed broadband packages with speeds of 1 Gbps and over their FTTH networks.

Likewise, there is a widespread and intensive use of services through the Internet by part of consumers. Furthermore, the pandemic context of year 2020 and 2021 has led to an increase in the use of telematic means to work. These facts, together with the increase in the number of active broadband connections, has resulted in a growth in data traffic recorded in 2021, which recorded a total traffic of 54 million Terabytes, compared to 46.3 million the previous year, a figure that represents increase of 16.7% in the last year.

The following graph shows the evolution, in the last seven years, of the volume of data monthly average per broadband line in Gigabytes. In the last year, the increase average monthly traffic per line was 31 Gigabytes compared to 2020, that is an increase of 13% to 269.16 Gigabytes. each broadband line generates data 269 GB of data per month and line.
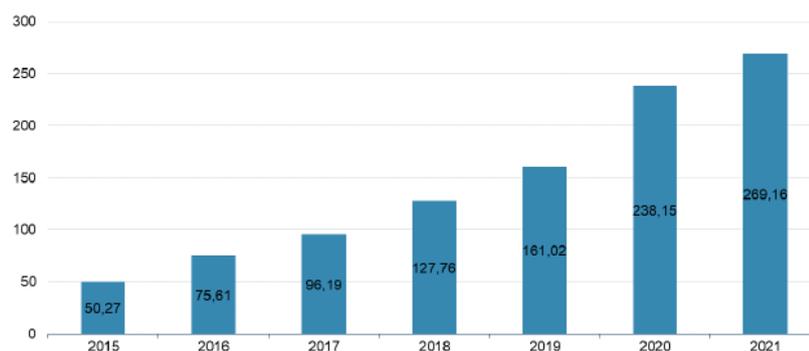
Fuente: CNMCData

Figure 3.3-4 Evolution of data traffic per broadband line (Gbytes/month/line)

Speed of the lines

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The following graph shows a growing evolution of the contracting of offers of broadband with higher speeds. The main factor that favors this increase in contracted speed is the improvement of the access networks and the commercial strategy of the operators that include higher access connection speeds in their packages fixed lines and greater volume of traffic in the case of mobile connections. Both Movistar and the rest of the operators (with the deployment of FTTH accesses and the update of the HFC to DOCSIS 3.x) promoted the contracting of broadband offers with higher speeds of connection. Likewise, despite the limitations of the copper network, there are still offers connection speeds (up to 30 Mbps) using VDSL technology (a mode of xDSL which allows higher connection speeds than ADSL).

At the end of 2021, lines with connection speeds greater than 30 Mbps significantly increased to a percentage of 90.5% (in absolute terms they reach 15.1 million accesses), compared to 81.8% the previous year. For its part, accesses with contracted speed of 100 Mbps or higher increased by 1.26 million accesses and they came to represent 88.9% of the lines (14.86 million accesses) compared to 84% of the year 2020. Likewise, accesses with contracted speeds greater than 500 Mbps added 7.25 million, 43.4% of the total broadband. 88.9% of the population (not of the territory) has access to broadband, understood as more than 100 Mb/s (that is, 11.1% do not have access).
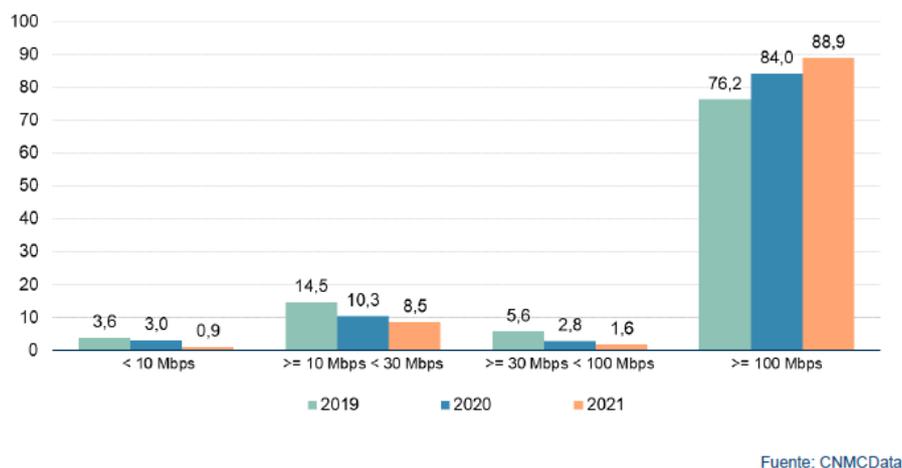
Figure 3.3-5 Evolution of broadband lines by contracted speed (percentage)

Voice calls

In 2021, voice traffic decreased by 1.7% compared to that declared the previous year. This drop was observed in all market segments, although differences were recorded in terms of its intensity. Thus, the postpaid modality registered an insignificant drop year–on–year of 0.7% of its voice traffic, while the prepaid segment had a significant drop of 12.6% in its traffic.

Registered traffic between mobile communications networks fell by 1.7%: traffic carried between different networks (off–net traffic) was reduced by 1.8%, while traffic within one same network (on–net traffic) grew by 7%. It should be remembered that most of the rates currently marketed also include call traffic in their quota terminated in fixed telephone networks. In this sense, the traffic linked to this type of calls decreased by 1.1% in the last year.

With regard to international communications, the demand for the service of international roaming grew by 12.2%, while international calling service decreased by 18.2%. The recovery of traffic linked to the roaming service international may be related to the fact that, in 2021, the authorities relaxed partially .

Total television consumption in 2021 was 214 minutes (3 hours and 34 minutes) per personand day. This data meant a setback of 27 minutes compared to the average consumption of 2020(Note that 2020 was a somewhat unusual year as the COVID pandemic and thereduced social mobility, favored an increase in television consumption forthat period).
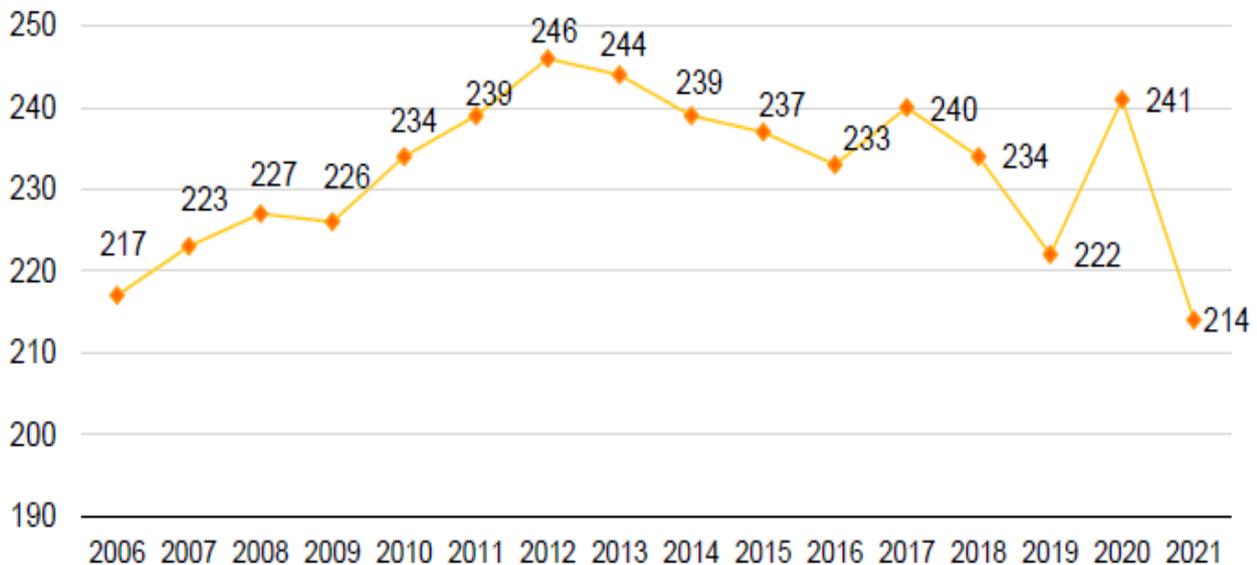
Fuente: Kantar Media

Figure 3.3-7 Average television consumption (minutes/person/day)

The 214 minutes per person per day were broken down into 199 minutes of linear consumption, plus 7minutes of delayed consumption (delayed consumption is measured since February 2015 and refers to the audience during the seven days following the linear broadcast) and 8minutes of guest consumption (guest consumption began to be measured in March2017 and includes the consumption of viewers who are not habitual residents of the home where they are watching television).

The total time of "television" consumption broken down by the type of platform used users to watch television, DTT services (which exclusively transmit free television content) accounted for 73% of the time spent by viewers to watch television, compared to 26%43 of the time they spent consuming content through pay television platforms (IP TV, cable TV and cable TV satellite).

Within payment platforms, IP TV technology was the one that achieved the highest share with 17% of viewing time, thus exceeding its historical maximum reached in 2020.For its part, cable television remained stable and satellite television fell toa fee of 1%.

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Figure 3.3-8 Broadcast audience (percentage)

4. Connectivity levels worldwide, and percentage of population in rural areas

4.1. Information on rural population

Exploring options for the 50% of the population unconnected to the internet as of the end of 2019, 46.4% of the world's population does not have regular access to the Internet. Bringing more than 3.5 billion individuals still unconnected online is the primary goal for multiple international organizations, including the ITU and the UN Broadband Commission.

Two important barriers that restrict connectivity are the lack of infrastructure and affordability. To address these barriers, several novel concepts that involve spaceborne and airborne platforms have been proposed to provide connectivity at a lower cost (improve affordability) to a wider reach of people (extend infrastructure). Development a techno-economic methodology to assess the potential impact of space and aerial concepts in expanding connectivity to uncovered and under-served regions. In particular, constellations of geostationary orbit (GEO)satellites, large constellations of medium Earth orbit (MEO) and low Earth orbit (LEO) satellites, and high- and low-altitude aerial platforms are studied.

Results show that under the current scenario, the impact of space and aerial systems in terms of expanding connectivity would be rather modest; the current cost of satellite technology (~$200 per Mbps/month) are affordable for less than 1% of the uncovered and under-served population in the countries of interest. In a future scenario in 8–10 years, space systems have the highest potential to bring uncovered and under-served populations online, being a viable technology for 24% of the population in these countries.
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Telecommunication services have significantly impacted technological progress, economic growth, and social dynamics in the last century (International Telecommunication Union (ITU), 2018). In recent years, the widespread adoption of the Internet has resulted in a new economy, where the focus has shifted from manufacturing towards technology-based companies, and where innovation in the form of new products and services has supported economic and wage growth (Broadband Commission for Sustainable Development, ITU, UNESCO, 2018).

However, not everyone equally is benefiting from this new economy. To date, 46.4% of the global population is still offline (International Telecommunication Union (ITU), 2019), and even though most of them live in areas covered by 3G and 4G connectivity, approximately 11% of the population live in areas with no coverage at all. Most areas with no broadband connectivity are in the least developed countries in Africa, South America, and Southeast Asia. Two main reasons for the absence of connectivity are the lack of infrastructure and affordability issues. Due to the sparse distribution of the population and their relatively low incomes, traditional communications systems, such as copper and fiber optic lines, are not well-suited for extending connectivity into these regions since they are expensive to deploy and have limited coverage. Thus, new concepts such as satellite constellations, networks of interconnected balloons or unmanned aerial vehicles (UAV), and tethered blimps have been proposed in the last few years (Space Exploration Holdings, 2016; TelesatCanada, 2016; WorldVu Satellites Limited, 2016; Bleicher,2018; Sundaresan et al., 2018).

As showed previously fixed and mobile broadband have had a significant impact on the global economy. An increase of 1% in fixed-broadband connectivity yields an increase of 0.08% in GDP, whereas a similar increase in mobile-broadband penetration results in an increase of 0.15% in GDP. However, by the end of 2019, only 53.6% of the world's population was connected to the Internet (International Telecommunication Union (ITU), 2019); bringing online the other half is a stated priority of various international organizations, such as the ITU Resolution 200 - Connect 2020 Agenda for Global Telecommunication/ICT Development (Union, 2014) and the UN Broadband commission (Commission, 2018). The main goals of these two groups are to find scalable and replicable solutions to connect large rural offline populations at minimal costs and to find effective strategies for narrowing the usage gap across all regions.

Several studies have been conducted to determine the main factors which influence the number of people connected to the Internet in a given country. These studies identified techno-economic factors such as the degree of infrastructure roll-out (i.e., communications infrastructure, road infrastructure, power infrastructure) and affordability(i.e., device cost, service cost, electricity cost) as the two most important factors to be solved through technological innovations, while policy factors such as relevance (i.e., access to content in their primary language, perceived value of Internet use) and readiness (i.e., information technology skills, know-how, basic literacy) also play an essential role. Affordability and infrastructure roll-out are closely related. Telecommunications operators do not deploy infrastructure in areas where business opportunities are not viable, and low-income individuals have few incentives to subscribe to broadband services.

Deploying new infrastructure becomes increasingly complicated when the geographical distribution of those unconnected and their income levels is taken into account. 45.7% of the world's population lives in rural areas, and it is estimated that the poverty rate in these regions is three times higher than in urban areas. Therefore, bridging the connectivity gap will require technologies that allow for sparse populations to be connected in cost-efficient manners. New low-cost and wide-coverage solutions are an active area of research in both academia and industry, and several concepts have been proposed, developed, and tested within the last few years. Most of these new concepts differ from

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traditional broadband connectivity solutions (i.e., terrestrial systems like fiber, cell towers, or mm-wave links) in that they make use of space and aerial platforms to provide connectivity.

The main goal of this section is to understand and identify space and aerial systems that can be used to expand broadband globally, and to quantify the impact (in terms of coverage capabilities and cost) of these newly-proposed concepts. This will require the analysis of both technical and economic factors, as well as comparing these systems to current terrestrial systems. Of the 46.4% of the population that is offline, we focus on the subset that has no connectivity at all or only 2G connectivity (i.e., under-served). This represents ~60% of the Earth's inhabited surface and contains 12.9% of the population. Specifically, the results presented herein focus on answering the following question: What is the potential impact of space and aerial systems in terms of connecting additional populations?

The answer to this question can be leveraged by policy-makers to decide on what areas and technologies should policies to expand connectivity to uncovered and under-served regions focus.

Despite the remarkable advancements made in terms of connectivity within the last ten years (driven mainly by the widespread adoption of cellular communications), almost half of the world's population still lacks connectivity. Termed as the digital divide, this is considered as one of the most pressing issues that needs to be resolved by the international community in order to guarantee equal access to opportunity. Although there are many different definitions of the digital divide, the common desired impact is to achieve benefits from deploying information and communications technologies (Hilbert, 2011).

To raise awareness of the importance of expanding broadband connectivity and boost the issue's prominence within the international policy agenda, the ITU and The United Nations Educational, Scientific and Cultural Organisation (UNESCO) set up the Broadband Commission for Digital Development in 2010, whose main tasks include advocating at the international level for the expansion of broadband, defining target connectivity values to be met, and conducting progress monitoring, evaluation, and reporting activities.

The latest targets defined in 2018 (Broadband Commission for Sustainable Development, ITU, UNESCO, 2018) that this paper will focus on are as follows:

1. By 2025, entry-level broadband services should be made affordable in developing countries, at less than 2% of monthly gross national income (GNI) per capita.

2. By 2025 broadband-Internet user penetration should reach 75% worldwide, 65% in developing countries, and 35% in least developed countries

Out of the 4.1 billion connected users, 1.1 billion are fixed broadband users, whereas 3.5 billion are mobile broadband users (UN Broadband Commission, 2017). Among those not connected to the Internet (i.e., 46.4% of the population), ~70% live in areas where mobile broadband connectivity (3G/4G technology) is available. Next figure shows the distribution of offline users by region and country1.
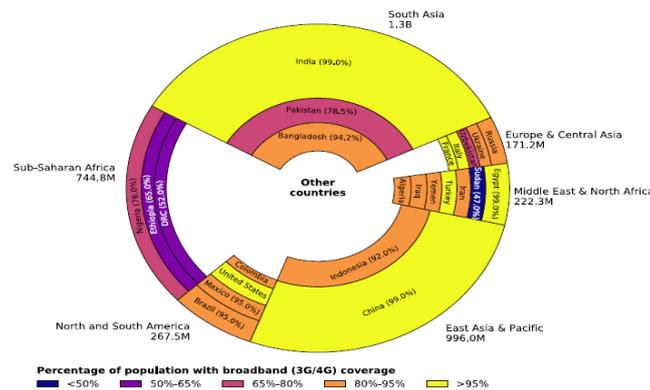
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Figure 4.1–1 Total population unconnected 2018. Distribution of offline users vs. percentage of broadband coverage at the end of 2018

The area of each wedge is proportional to the absolute number of people unconnected, whereas colors indicate the percentage of the population with broadband coverage on each country. The image highlights that the usage gap (i.e., those living in areas covered by

mobile broadband networks but are not connected) is several times larger than the coverage gap (i.e., those living outside of areas

4.2. Space and aerial systems to expand connectivity

With the first wave of LEO mega constellations in the '90s, significant effort was made to determine both the technical and economic feasibility of space systems and their constellation designs. Shaw (1998) developed GINA, a generalized framework for evaluating information networks, and used it to assess the designs proposed by Cyberstarr, Spaceway, and Celestri. GINA integrated it with a multi-disciplinary design optimization (MDO) framework, which he used to conduct trade space exploration of LEO, MEO, GEO satellite systems. Kelic (1998) and Gumbert (1996) proposed the "cost per T1 link-per-minute" as a metric to assess the financial viability of broadband satellite systems, and used it to study five GEO and LEO systems. Alternatively, used the total cost of ownership for five years to calculate the average cost per user in two GEO satellite scenarios. Finally, proposed a methodology for trade space analysis of LEO personal communication systems, that combined technical, economic, and policy aspects with which analysed how staged deployments can be used to reduce risks associated with the uncertainty on demand. Regarding newly proposed systems, was compared from a technical standpoint the constellation designs of SpaceX, OneWeb, and Telesat.

Aerial systems, both high altitude platform (HAP) stations and low altitude platform (LAP) stations, have long been considered as a candidate solution to extend the reach of communication networks since they can cover larger areas compared to terrestrial systems.

On the one hand, a HAP is seen as a middle ground between terrestrial and space systems, which exploit the advantages of both: providing large coverage areas (100–10,000 km2), requiring a small number of base stations, having low interference due to building sand terrain obstructions, low latency, rapid, incremental, and localized deployments, ease of maintenance, and potential for reconfiguration. Research in the use of HAPs as a platform for communication services boomed in the 2000s after ITU'sWRC–97, where the spectrum allocation for HAPs services was adopted by over 50 countries. The role of HAPs within the global connectivity landscape and their interactions with existing

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infrastructure (terrestrial and satellite) was the focus; other analyse the coverage problem (i.e., the number of HAPs required to provide coverage to a particular region) for selected countries.

On the other hand, even though the principal use cases for LAPs have been to facilitate rapid recovery of damaged terrestrial wireless infrastructure due to natural disasters, to augment wireless networks to cover foreseen massive crowd movements, and for temporary military deployments, in recent years several commercial companies have proposed using LAPs to provide long-term communication infrastructure in rural and low-population density areas. With the increasing popularity of low-altitude UAVs, some cell phone companies have studied the use of "swarms" of UAVs to form low-altitude networks that extend the existing terrestrial networks.

However, there is a lack of analysis involving trade space exploration while taking into account the economic feasibility of the different systems. This is mainly due to the lack of reliable economic models for these systems, which are in an incipient stage of development.

The 12.9% of the population that has no connectivity (i.e., uncovered) or only 2G connectivity (i.e., under-served) are spread out across more than 50% of the inhabited land area on Earth, making it extremely challenging to provide connectivity to them using terrestrial infrastructure. To this end, space and aerial concepts lend themselves better to providing connectivity to those uncovered.

This section proposes a methodology which can be applied to both space and aerial concepts, to evaluate the viability of each concept in bringing connectivity to uncovered and under-served settlements and regions.

This section presents and discusses data highlighting the barriers to connectivity. Numerous studies have concluded that barriers to adoption can be classified into four groups:

- lack of infrastructure,
- affordability,
- readiness, and
- relevance.

These barriers rarely exist in isolation, and overcoming them would require both technical- and policy-oriented actions to be carried out collaboratively by all the stakeholders involved (industry, governments, non-governmental organizations (NGOs), and non-profits).

Next figure shows Movistar 5G coverage in Spain as an example of all declared above.

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Figure 4.2–1 Movistar Movil 5G coverage map, Spain

4.3. Rural settlements

All the maps produced on the rural habitat repeat a common message: in Galicia and Asturias there are many small population entities, the majority, compared to the larger towns and villages as you go south, east and especially in regions with flat topography. This is confirmed in the 2015 Rural Population map. Rural settlements are those with fewer than 10,000 inhabitants, something doubtful in some cases with county heads such as Redondela, Noia, Ribadeo, Luarca or Ribadesella. In any case, the percentage of the total provincial population is above 40% in Galicia and in provinces of both Castillas with small capital cities (Zamora, Segovia, Ávila, Soria, Cuenca, Toledo), while its Representativeness does not reach 20% in the urbanized provinces of Madrid, Barcelona, Valencia, Seville, Malaga or Bizkaia, among others.
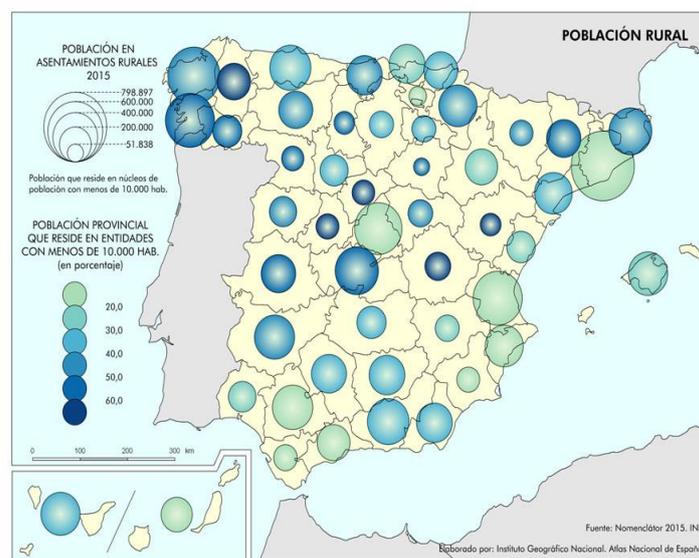
Figure 4.3–1 Rural population map. 2015. Spain

This map is completed with a second one that maps the scattered population, meaning scattered villages with few houses, and that confirms the predominance of this type of settlement, again, in Galicia, although also in numerous Mediterranean territories, where urbanization generalized and with little control, and a shifted relief, justify percentages between six and nine percent (Illes Balears, Murcia, Almería, Castellón). Finally, the singular population entities by municipality are presented, where figures above 40 stand out in Galicia and Asturias, a little lower in Murcia, and records of less than 2.6 entities per municipality in Extremadura, a good part of both Castillas, La Rioja , Zaragoza and Teruel, Seville and Malaga, Valencia and Alicante, reflecting the Spain of concentrated habitat.

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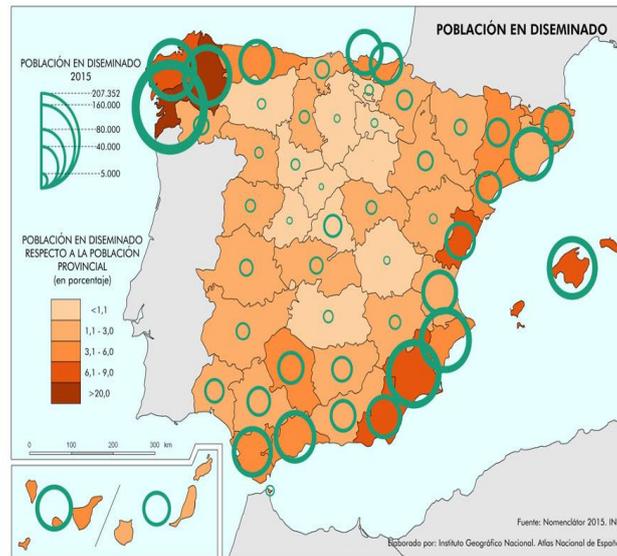
Figure 4.3-2 Disseminated population map. 2015. Spain.

On the Settlement Density map, in which population entities are represented every 10 km2, note that the maximums are concentrated in the north of Galicia, the Baixas estuaries, Gijón–Avilés and the center of Asturias. The high values do not usually exceed Atlantic Spain, although in Catalonia, the coasts of Valencia, Alicante and Murcia, the surroundings of Madrid and large areas of rural Salamanca, records between 10 and 20 unique entities per 10 km2 predominate. The map Population in disseminated by municipality represents the population in disseminated with respect to the total and here the most important conclusion refers to the peripheries–interior contrasts of the country, although not necessarily the coastline. Leaving almost all of Galicia aside, the values exceed 10% in significant sectors of the Cantabrian regions, northern Catalonia, a strip that goes from the west of Castellón to Murcia and Almería and important areas of Málaga and Cádiz. These are mountainous spaces, where recent construction processes have been recorded, linked to the tourist boom of large territories of the coast and its backcountry.
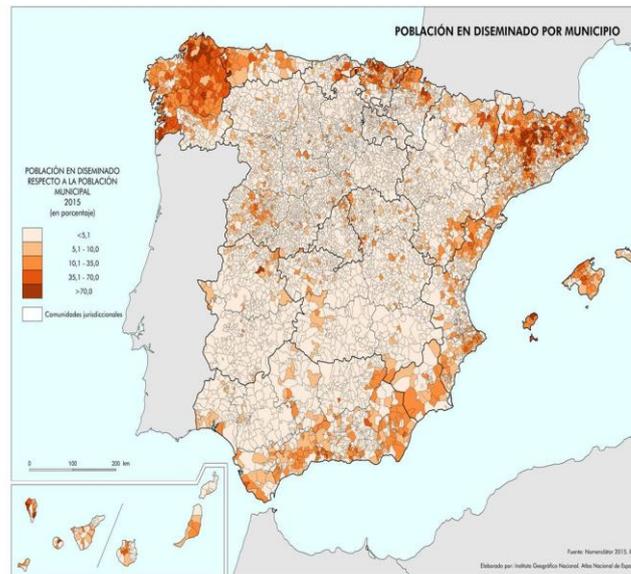
Figure 4.3–3 Population map spread by municipality. 2015. Spain.

The Population in rural settlements map presents the Spanish municipal population in 2015 living in nuclei with fewer than 10,000 inhabitants, although the municipality as a whole could exceed 10,000 inhabitants. The most relevant conclusion that can be drawn from this map refers to the high number of municipalities with less than 2,000 inhabitants in the interior of the peninsula and the significant weight of the scattered population, even in municipalities with more than 10,000 inhabitants, in the periphery and halo. of the great metropolises.

Figure 4.3–4 Population map in rural settlements. 2015. Spain.

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5. Summary and Conclusions

HAPs offer an effective way of exploiting mm-wave spectrum by supporting multi-cell architectures. The viability of such systems is largely determined by the overall system data capacity, which is in turn governed by the properties of the antenna payload which serves the cells on the ground. In previous studies, "ideal" antenna beams have been used to model carrier-to-interference ratio. In such cases, dedicated aperture antennas such as lens antennas may be used to produce the required beam shapes which are in general asymmetric.

Using multi-beam antennas lenses mass and volume of the HAP payload can be much reduced. A convenient approach is to employ spherical lens antennas using multiple feeds. This work has considered the properties of such antennas and shown Disadvantages of this antenna type is that radiation patterns are in general of circular cross-section, which leads to non-circular cell footprints, and a compromise beamwidth must be chosen for a given cell group.

While operational HAP communications services have yet to be deployed in practice, it has been shown that a group of multi-beam spherical lenses could offer a very practical and compact antenna payload. This would support multi-cell architectures with adequate levels of co-channel interference and with a very considerable mass saving compared to a payload of a type which uses one lens antenna for each cell.

Summary of the expectations of this concept in comparison with already presented approaches.

Advantages	Disadvantages
Total number of radiating elements is lower Number of active elements in forming a main beam is significantly reduced. Excellent side lobes suppression is provided by lens itself. It is not necessary to employ any amplitude or phase distribution except the phase shift or delays for the beam scan. Wide main beam scan range with almost constant properties or very small losses Expected costs are significantly lower Commercially proven materials available for lens manufacturing Main beam scan is performed by switching of certain number of radiating elements in combination with a small conical scan of few degrees Implementation of DBF concept is much easier due to reduced number of elements to be processed simultaneously	Depending of required antenna gain the dielectric losses could degraded significantly G/T. Over sizing of lens result in a bulky solution. A proper selection of lens material is a key factor for this concept implementation The use of a small number of active elements implies the use of a higher power amplifier by the unit radiating element or the transmission system should be designed as a PESA (passive electronic scanning antenna) oversizing the total RF power to compensate switching network losses. Possible difficulties in its implementation.

Table 5-1 Summary of the expectations of this concept

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