HORIZON-MSCA-2021-DN-01

ANTERRA
101072363

Literature report on state-of-the-art NTN antenna technology

Deliverable D2.1

V2.1

Document history – List of changes

Version	Date	Author name	Scope
V0.1	10/06/2023	Diego Caratelli	Table of contents is defined
V0.2	27/06/2023	Ph.D. Students	Draft of the document is available
V1.0	30/06/2023	Ashifa Mohammed Musthafa	Final formatting and cross-referencing
V2.0	13/12/2023	Jan Haagh	Changed ‘MSCA-2019’ to ‘MSCA-2021’
V2.1	20/12/2023	Jan Haagh	Updated Acknowledgement text, EU logo and call identifier

Contents

Funded by the European Union

Funded by the European Union, under ANTERRA 101072363 HORIZON-MSCA-2021-DN-01. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

1 Introduction

Non-terrestrial networks (NTNs) have emerged as a promising solution to extend global connectivity, especially in remote and underserved regions. The success of these networks heavily relies on the development of efficient and advanced antenna technologies. This literature report provides an overview of the state-of-the-art non-terrestrial network antenna technology, highlighting the key advancements, challenges, and future prospects. The report covers various types of NTN antennas, including satellite-based antennas, high-altitude platforms (HAPs), and drones, and discusses their design principles, performance metrics, and emerging trends.

1.1 Overview of non-terrestrial networks and their significance

The domain of non-terrestrial networks (NTNs), representing all communication networks outside the terrestrial atmosphere, has seen a remarkable rise in both attention and deployment in the recent period [1]. The next-generation of wireless networks, i.e., 6G, is expected to go beyond terrestrial frontiers, incorporating non-terrestrial networks (NTN) to achieve ubiquitous global coverage [2]. These networks are generally comprised of satellites, High Altitude Platforms (HAPs), Unmanned Aerial Vehicles (UAVs), and other space-based communication assets [3]. It offers a multitude of benefits in the realms of global connectivity, data transmission, emergency services, and more. Some brief overview of NTN components is given below.

Satellite Networks: Satellite networks form the crux of non-terrestrial networks and have been in operation for several decades [4]. They are primarily used for wide-area network coverage and are indispensable for global positioning services, international broadcast, and data transmission. With advancements in technology, we now have low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary Earth orbit (GEO) satellites, each with their own unique operational aspects and benefits.

HAPs and UAVs: Emerging components in the NTN system include High Altitude Platforms (HAPs) and Unmanned Aerial Vehicles (UAVs) [5]. HAPs operate in the stratosphere and are usually solar-powered, capable of staying aloft for extended periods. They can provide localized coverage for communications, acting as pseudo-satellites. UAVs, popularly known as drones, can also provide localized network coverage in remote or inaccessible areas, playing a critical role in times of emergencies.

Integration with Terrestrial Networks: The integration of these non-terrestrial networks with terrestrial 5G and beyond networks (B5G) is expected to yield more comprehensive, resilient, and ubiquitous network coverage [6]. This will facilitate better connectivity, ultra-reliable and low latency communications (URLLC), and massive machine-type communications (mMTC).

1.1.1 Significance

Some of the role and significance of NTNs can be encapsulated as following:

a) ***Global Connectivity:*** Non-terrestrial networks have the potential to offer truly global network coverage. With a well-designed array of satellites or HAPs, it's feasible to provide connectivity to every corner of the globe, including remote and rural areas where terrestrial network deployment is impractical or economically unviable.

b) ***Disaster Recovery and Emergency Services:*** In situations where terrestrial networks might fail or become compromised, such as during natural disasters or extreme weather events, non-terrestrial networks can provide essential communication channels for relief efforts and emergency services.
c) ***Network Resilience:*** Non-terrestrial networks can enhance the overall resilience of global communication infrastructure, acting as backups when terrestrial networks encounter disruptions.
d) ***Ubiquitous & High-Speed Connectivity:*** The integration of non-terrestrial networks with 5G and future generations of networks is anticipated to enable high-speed internet and low-latency services everywhere, resulting in improved user experiences and enabling advanced applications such as remote surgery, autonomous driving, and more.

In nutshell, NTN communication systems will be instrumental in realizing the future vision of ubiquitous connectivity, facilitating innovative applications, and ensuring network resilience in times of crises. Thus, the study and development of non-terrestrial networks are not only significant but essential for the advancement of global communications [6].

1.2 Importance of advanced antenna technology for non-terrestrial communication

NTN are the key component to satisfy the demands of worldwide coverage, greater speed of data transfer and ensuring service availability, continuity and scalability in the future 6th generation of mobile communication [7]. The communication framework between satellites/airborne with the current deployed terrestrial network has become a fundamental factor under research to provide the desired performance [8]. Last years, in each generation of communication networks, terrestrial networks have been reused and upgrade it from the previous one with the objective to minimize the costs without compromising the performance. Currently, with the new paradigm of NTN, to get profit from this joint between terrestrial networks and NTN, it is required a lot of effort in the satellite/airborne communication system design point of view to provide the desired performance while being well compatible with the terrestrial networks [9]-[10].

Despite the advantages of the deployment of NTN, it brings about its challenges such as propagation channel and delay, frequency/bandwidth allocation, link budgeting, mobility of the satellite/airborne and user equipment [10]. In consequence, the role associated with the antenna system is gaining importance in the NTN communication design to provide the features of 6G by overcoming the aforementioned challenges. In fact, the design of the antenna can have a huge impact on the performance of NTN networks and can pave the way for the rise of NTN networks. The NTN framework is based on satellites such as low/medium/geosynchronous Earth orbiting (LEO, MEO, GEO) satellite or airborne (UAV and HAPS). The requirements associated with the antenna system on each of them are slightly different and they are highly dependent on several constraints such as the velocity, power, altitude, size and the role of each of them in the NTN network [11].

Satellite NTN communication plays the role of providing worldwide coverage by ensuring service continuity and acts as a backhaul connectivity of terrestrial networks. They are located at high altitudes, between 300 km to 35786 km, which suffer high propagation losses and hence they feature considerable delay of data transmission [7],[9].Therefore, it is required advanced antenna technology that can provide huge gain and EIRP to minimize the high propagation losses, very broad bandwidth to provide high data rates, and huge number of simultaneous beams to improve the frequency reuse capabilities [7],[9],[12] .The satellite operates at the mm-Wave band, especially at the Ka-band, which allows to design small antennas with effective cost and provides high gain and the chance to use a wide spectrum bandwidth. To counteract the high path losses and hence to provide high gain and EIRP, large antenna arrays should be used [6].

The future mega-constellations of NTN satellites will be interconnected with inter-satellite links (ISL). Inter satellite links could be radio links or optical communication links. Nowadays, some studies that explore the possibility of the use of Intelligent reflecting surfaces (IRS) well known as reconfigurable intelligent surfaces (RIS) join with THz band in LEO ISLs. On the other side, optical communication links have been proposed for the ISL because of their greater energy efficiency compared with RF links [11].

During the last years, phased array technology has emerged as a demanded design for satellites, instead of array-fed reflectors, where directional high gain beams could compensate the high path loss at mm-Wave band. Nowadays, thanks to recent technological advancements in the space industry have demonstrated that phased arrays using electrical beam steering or beamforming are beneficial in terms of cost, complexity and overall system performance compared to fixed antenna apertures with mechanical steering [7] [9].

The airborne category includes unmanned aircraft vehicles (UAV) and high-altitude platform systems (HAPS). They are intended to be used as a repeater node between satellites and user ground terminals, as an aerial user or as an aerial backhaul link. They are located at low altitudes, less than 20 km and the propagation delay and path losses are in the range of terrestrial communication but each of them has different limitations of payload weights and sizes [6]. Currently, the research on the antenna technology deployed at HAPS and UAV is based on achieving the largest possible terrestrial coverage, by providing high gain in a wide range of directions with the minimum size and weight [13]. Mostly, they use several panels whereby using beam steering allows them to cover areas further away from the broadside. Beam steering antennas allow to reduce the size and weight compared with the typical mechanical antennas. For instance, recently in the literature, it has been proposed some advanced antenna designs such as a planar active electronically scanned array (AESA) antenna [14].

For the ground user equipment (UE) or ground base station, antenna design requirements could be relaxed further by the intensive effort applied in satellite/airborne antenna design and for its limitation [15]. In user terminals two types of users can be distinguished: The first one is handheld devices with Omni-directional antennas and the other one is the very small aperture terminals (VSAT) with directional antennas. Handheld devices should work in lower frequency bands such as S-band to connect with terrestrial networks and at higher frequency bands such as Ka-band to connect with the non-terrestrial network directly. Therefore, new antenna technology presenting dual-band operation should be required. Contrariwise, VSAT terminals will operate at higher frequencies such as Ka-band requiring higher bandwidth and the use of directional antennas with higher gains and beam steering to connect with the satellite/airborne nodes [3]. The capability of beam selection at UE can avoid suppressing the effect of interference and maximize the signal quality. In fact, the gain of the User terminals is a very important metric in the link budget of the NTN [16].

Nowadays, as aforementioned advanced antenna technologies are highly demanding and in constant research to provide the NTN desired performance. The characteristics of these advanced antenna technologies are associated with the number of simultaneous beams, polarization, maximum scanning angle, operational frequency, bandwidth, beam gain, beam EIRP and required dimensions. In fact, the current research in advanced antenna solutions is to implement multi-beam antennas that send the information to different spots on the ground through a plurality of beams, thereby maximizing spectrum efficiency through spatial diversity and charging multiple users simultaneously and covering a wide area [7][13]. To avoid the overlapping of the beams and interference among them and maximize efficiency, it is tried to steer the beams to high beam scanning angles up to 60º [11],[17].

1.3 Definitions and acronyms

AM	Additive Manufacturing	ISL	Inter-Satellite Links
DNG	Double Negative (materials)	SLM	Selective Laser Melting
DMLS	Direct Metal Laser Sintering	RIS	Reconfigurable Intelligent Surfaces
DRA	Dielectric Resonator Antenna	AESA	Planar Active Electronically Scanned Array
EBG	Electromagnetic Band Gap	UE	User equipment
EM	ElectroMagnetic	VSAT	Very Small Aperture Terminals
MAM	Microwave-Absorbing Material	MBA	Multi Beam Antenna Payload Antennas
NTN	Non-Terrestrial Network	UAV	Unmanned Aerial Vehicle
LEO	Low Earth Orbit	QoS	Quality of Service

HAP	High-Altitude Platform	ML	Machine Learning
SINR	Signal-to-Interference-and-Noise Ratio	ISNR	Interference-to-Signal-and-Noise Ratio
FDM	Frequency Division Multiplexing	ITU	International Telecommunication Union
IRS	Intelligent Reconfigurable Surface	MIMO	Multiple-Input Multiple-Output
EOC	Edge of Coverage	EIRP	Effective Isotropic Radiated Power
HPBW	Half Power Beamwidth	A-BFN	Analog Beamforming Network
D-BFN	Digital Beamforming Network	HAP	High Altitude Platforms
SFB	Single Feed per Beam	PIN	Positive Intrinsic Negative
FAFR	Focal Array Fed Reflectors	SLA	Stereolithography
DRA	Direct Radiating Active	SM	Subtractive Manufacturing
BS	Base Station	SBS	Small Base Station
RAN	Radio Access Network	MEO	Medium Earth orbit
GEO	Geostationary Earth Orbit	SAT5G	Satellite and Terrestrial network for 5G
HPA	High Power amplifier	RF	Radio Frequency

2 Satellite-based Antennas

2.1 Characteristics and design considerations of satellite antennas

Over the years, antenna engineers, whether the antennas are employed on Earth or in space, have relentlessly worked to introduce new antenna design solutions. These new solutions generally aim for improvements in cost, size, power consumption, design complexity, reliability, and manufacturing tolerance. Additionally, these antennas, if employed in space, are expected to fulfill the needs of the ever-changing next-generation satellite communication systems concerning system capacity. Besides, the satellite antennas are expected to act as a spatial filter to focus the beam in the desired area on Earth. So, the radiation pattern of space-borne antennas is accurately characterized for the entire mission period by accounting the pointing errors, spacecraft distortions, attitude instabilities, antenna misalignments, etcetera.

2.1.1 Design Considerations

Link Budget: Antennas, both space-borne and ground-based, play a significant role in the determination of the link budgets, and it is due to their ability to control the quality of service and availability and to enhance the system capacity. The size and mass are the key constraints of an antenna mounted on a satellite, which in turn constitutes the gain of the antenna. For a geostationary satellite antenna, the peak and the edge of coverage (EOC) gain, and effective isotropic radiated power (EIRP) on transmit, a high half power beamwidth (HPBW) and signal-to-noise ratio (S/N), or G/T on receive is the primary figure of merit. On the contrary, for the LEO satellite antenna, the scanning angle, gain, power consumption, extent of integration, and radiation purity is the immediate figure of merit.

The implications on the space environments: During its operation, a satellite antenna is in prolonged exposure to the harsh space environment, which includes vacuum, extreme temperatures, static charges, and debris. In addition, the antenna also needs to survive vibrations, shock, intense acoustic pressure, and depressurization during launch. Besides, structural deformations due to multiplication, material outgassing, creep, atomic oxygen, and material charging (particularly in LEO), need to be accounted for during the design process.

2.1.2 Antenna types and its specific requirements

Ultra-high frequency (UHF) satellite communication antennas: UHF antennas, typically used for military applications, cover the frequency band between 300MHz and 1 GHz and have the coverage required to cover the visible portion (about 17.4-degree diameter circular coverage) of the Earth's surface and a transmit/receive isolation of about 60dB. Additionally, the antennas tend to be electrically small relative to their long wavelength however have a large effective aperture to reproduce a high gain radiation beam. At UHF, the multipactor effect can be an issue.

L/S-band Mobile Satellite Communications Antennas: L-band antennas, typically used for mobile satellite applications, cover the frequency band between 1 GHz and 4 GHz and are expected to support the system to have a high link margin to guarantee high quality of service. Moreover, the antennas tend to be large, typically a parabolic reflector, and are illuminated with an array of feed elements to form several spot beams to cover a part of the coverage location. Each beam has a suboptimal EOC gain to manage the high spillover losses. The beams are formed using analog beamforming (A-BFN) or digital beamforming (D-BFN) networks. Due to the size of the reflector, deformation or single-point failure due to a deployment error can be an issue.

Ku and Ka-band FSS/BSS Antennas: Ku and Ka-band antennas, typically used for indirect access communication applications, cover the frequency band between 12 GHz to 40 GHz with typical bandwidths ranging from 250MHz to 1 GHz and, Ka-band broadband systems, up to 1.5 GHz. The power handling capability of these antennas a stringent and demands a very challenging design constraint. Moreover, the antennas tend to be large, typically a parabolic reflector, and are illuminated with a feed element to form a beam to cover a major part of the coverage location. Due to the size of the reflector, deformation or single-point failure due to a deployment error can be an issue [18].

2.2 Evolution from traditional geostationary satellites to LEO constellations

The history of satellite communication begins in 1945 with the article of Arthur C. Clarke, in which he described the purposes of a satellite communication system, how it could be launched, and why it should be placed in geosynchronous orbit. However, I took another 12 years until the first earth-orbiting satellite was launched, *Sputnik 1*. This launch by the Soviet Union was considered by the Americans a political act, and a few months later, the Americans also launched a satellite successfully. Multiple satellite launches were followed by both nations. In 1958 the first communication satellite, known as *SCORE*, was launched by the Americans, which could broadcast a brief message from the President. A few years later, in 1960, the first passive communication satellite *Echo 1* was launched by AT&T Bell Labs. This launch concluded that a passive satellite is not commercially viable. Two months later, the first active communication satellite was launched allowing transmission of 16 teletype channels. In 1962, the world's first private communications satellite was launched into the low Earth orbit (LEO) demonstrating real-time television signal transmission. A few years later, the first continuous satellite communication link was demonstrated with the *Intelsat Earlybird* satellite. Followed by satellites that provided satellite broadcasts to TV stations and mobile services in 1975 and 1976, respectively [19]. Between 1995 to 1997, the *Iridium* satellite constellation was launched, operating 66 satellites in six LEO orbits. Unfortunately, the *Iridium* system went bankrupt due to marketing, licensing agreement, and technical performance problems. Also, similar follow-up systems, such as the *Globalstar* system, which started operating in 1998 with 48 satellites in the LEO, and the *ICO* system, which was planned to be deployed in the medium earth orbit, went bankrupt [19],[20]. Similar systems, which all failed due to bankruptcy or cancellation, can be found in [21]. As a consequence, new LEO satellite constellations were not planned for many years. Nevertheless, new proposals for new constellations have arisen in the last decade. For instance, SpaceX intends to launch one of the largest mega-constellation with over 42000 LEO satellites forming the *Starlink* system and addressing worldwide broadband internet access. While the *Starlink* constellation started deploying and already operating on a smaller scale, many other constellations are planned by other companies. *OneWeb* initiated to launch 648 satellites aiming for global coverage. However, in 2020, also *OneWeb* went bankrupt due to the high costs of manufacturing and launching satellites. Further, *Telesat* intended to provide global coverage and high-throughput broadband capacity on LEO constellations, starting launching of the first satellite in 2018. The *Kuiper* project plans to launch 3236 satellites forming an LEO constellation to provide broadband connectivity for uncovered users. Many more constellations are planned for the future, a list can be found in [21].

Table 1: Selected history of the satellite communication (not complete) [19,20,21].

1945	Arthur C. Clarke firstly described a satellite communication system in his article
1957	The launch of the first Earth-orbiting satellite, Sputnik 1
1958	The world's first communication satellite was launched, SCORE
08/1960	The first passive communications satellite, Echo 1, was launched by AT&T Bell Labs
10/1960	The first active communications satellite, Courier 1B, was launched
1962	The world's first private sector LEO communications satellite, AT&T's Telstar
1965	Intelsat Earlybird, the first continuous satellite communications link
1975	First satellite broadcast to cable TV stations worldwide
1976	Marisat, the first communications system to provide mobile service
1995-1997	Launching and operational start of the Iridium satellite constellation (went bankruptcy)
1998	Deployment of Globalstar (went bankruptcy)
2018	SpaceX and Telesat launched Demo sats for their constellations
2019	Annoucement of the Kuiper project
2023 - today	Ongoing plans, developments, and deployments of LEO constellations

2.3 Advancements in antenna technology for LEO satellite networks

In the last decade, low Earth Orbit satellites (LEO) have become an attractive option for their provided reduction in operation, launch cost and energy consumption. In addition, LEO satellite communications present the advantages of reduction of propagation path loss, wide coverage, full connectivity and low latency communications [9] [12]. Nowadays, thanks to recent technological advancements in the space industry and academia, some advanced antenna research has been carried out in satellite communications, namely the interconnection between satellites and the link communications between satellite and ground terminal users.

Recently, has been demonstrated that a cooperative communication paradigm seems to be the more efficient and effective use of a network with such many small satellites. Therefore, the requirements for satellite antennas have been redefined to suit the high number of small satellites with relatively low power transmission capacities and requiring antennas with wide bandwidth, low cost, low profile, high port-to-port isolation and lightweight [22] [23]. During the last twenty years, antenna polarization has been adopted as one of the major features due to its promising performance. Since several years ago, antennas providing dual polarization have been widely used to enhance the channel capacity and reduce the influence of interferences. Accordingly, for LEO satellite communications dual circular polarization is well-demanded to provide an overall better performance.

Satellite communications with ground terminal users started to operate in L, C and S bands, but due to market demand for multiple beams applications, had envisioned operating in the mm-Wave band, especially in the K-/Ka-band which the downlink operates at the K-band and the uplink in the Ka-band [23] [24]. Last decade, several LEO satellite antennas based on different kinds of antenna elements, various kinds of reflector antennas, different array types, and various kinds of apertures have been studied in the literature [25]. During the 1990s multi beam antenna payload antennas (MBA) emerged as the most promising antenna design for LEO satellite communications because of their efficiency to reuse the frequency spectrum and high gain beams over the coverage region [26].

Firstly, it was proposed several designs based on using reflectors as an aperture, where they are in charge of compensating the spatial phase of the incident wave from the feeds and reflecting to a given direction [27]. A Single feed per beam (SFB) using high aperture efficiency horn or patch antennas for each feed, was proposed. On the downside, it requires several reflectors to obtain an optimal coverage performance [28] [29]. As a solution, it was proposed Focal Array Fed reflectors (FAFR) using beamforming to minimize the number of required reflectors. In FAFR each beam is generated using a group of elements placed in the focal region of a reflector, where it means that requires more elements than the number of beams. Although the elements are smaller than the ones used in SFB it was not a good design approach. All these designs are based on a reflector antenna approach which they scan the beam by mechanically moving the reflector or the feed or both simultaneously to the corresponding beam direction [30]. Additional time is required to steer the reflector, where could produce that in a very short time, the corresponding beam is not pointing in the required direction, hence being inefficient.

In addition, it was proposed mechanical steerable antennas where the antenna uses a fixed feed chain and mechanically the reflector is the only part that is moving to point the beams at the desired angles [28] [31]. Further, active discrete constrained lens antennas have appeared as a possible solution to generate multiple spot beams adopting only a single aperture. However, at this moment has not been considered a promising design for LEO satellites payload because of their high volume, weight and deployment issues [32].

In the early 2000s, phased array antennas or electronically steering antennas emerged where small radiators can scan the beam electrically by changing the phase of its elements instantaneously. Its promising features such as low profile, low power consumption, lower weight and overall good performance make it considered the most promising antenna design in the LEO satellite antennas even do having a huge complexity and cost. On the downside is required more active elements such as beamformers networks are in charge of controlling the excitation of the elements in the array [30]. At the beginning of this new paradigm, Direct radiating active (DRAs) emerged which the elements are shared between all beams and only is used a single aperture, but it was realized that the number of elements required is one order of magnitude higher than the reflector-based solutions [28] and present high complexity in the beamforming system. In addition, another limiting factor on phased array antennas is related to the large mass and high-power dissipation they require for large active phase array configurations.

Nowadays, thanks to recent technological advancements in the space industry and academia have demonstrated that phased arrays using electrical beam steering or beamforming are the most promising antenna design for LEO satellites because of being beneficial in terms of cost, complexity and overall system performance compared to fixed antenna apertures with mechanical steering [11] and others antenna design proposed until today. For the future mega LEO constellations of satellites, size and price of the launched satellites will be reduced and hence a deep study on phased array antennas with low weight, low size and low cost should be presented. Further, a ±60° beam scanning range should be required for the desired uninterruptible communication feature of NTN. Hence, the requirements for the LEO satellite communication antenna are comprehensive and not easy to achieve [33].

The radiating element, also known as unit-cell elements, and the architecture system behind the radiating elements such as beamforming network and High Power amplifier (HPA) elements, are receiving a lot of interest in research. One of the performances required is to provide a compact wideband radiating unit-cell, allowing to integrate both Rx and Tx within the same antenna and offering acceptable performance [33]. Many planar radiating elements have been proposed such as waveguide, tapered slot, dipoles, and microstrip path antennas, where the research on new types of radiating elements are being on research from the academic community and industry to obtain better performance. In the radiating element point of view, the selected design must satisfy the systems requirements in terms of bandwidth, polarization, gain and integrability [35].

The choice of the beamforming technique has been under study for the last few years. Fully analog or digital beamforming solutions have been proposed, but hybrid beamforming network solutions have emerged as a promising solution due to the possibility of featuring the tradeoff between system complexity and good performance, providing better performance than analog and digital beamforming techniques. Indeed, two basic implementations of the whole antenna array system, brick and tile configuration are under study. The brick configuration requires a considerable amount of Radio Frequency (RF) boards, adapters, and cables to route the RF, bias and control signals, but provides better heat dissipation of the active components. Tile configuration adds a high integrating component complexity to incorporate all required electronic components into the area occupied by the corresponding radiating element but lowers the construction depth and reduces the number of required connectors [35].

As the state-of-the-art technology of Inter-satellite links (ISLs), Terahertz communication with RIS and optical communication links has appeared as a promising solution for ISLs since it can provide high data rate communications and very low power consumption due to the lack of active elements [22].

2.4 Beamforming and phased array antennas for improved capacity and coverage

2.4.1 Introduction

Satellite communication is crucial for enabling connectivity across vast distances and reaching remote areas. Phased array antennas and beamforming techniques have gained significant attention to enhance the performance of satellite antennas. This section examines the principles, capabilities, and advantages of beamforming, the use of beamforming for improving capacity and coverage in non-terrestrial networks, and the antenna types used in phased array designs.

2.4.2 Literature Survey

Beamforming and phased array antennas have emerged as critical technologies for enhancing capacity and coverage in wireless systems, particularly in fifth-generation (5G) and sixth-generation (6G) networks. In [36], a new heterogeneous phased array architecture that combines antenna-on-display (AoD) and antenna-in-package (AiP) modules is presented. The proposed architecture achieves three independent multi-beam steering radiations in different directions by symmetrically arranging these modules, enhancing spherical beamforming coverage. The model demonstrates substantial improvements in equivalent isotropic radiated power (EIRP) compared to individual AoD and AiP modules. A study on ultra-thin, low-cost, electronically beam-scanning reflect-array antennas for Ka-band satellite communications on the move and 6G networks are presented in [37]. By employing a leaky-wave feed and printed unit cells with low phase resolution, efficient beam scanning is achieved while significantly reducing the thickness and cost of the reflect-array antenna. With increased aperture efficiency, the proposed architecture can be suitable for Ka-band satellite communications and future 6G applications.

[38] analyzes a millimeter-wave cellular network's capacity and signal-to-noise ratio (SNR) using a phased antenna array. The study highlights using millimeter-wave directional antennas with beam steering to achieve high data rates and capacity. Channel capacity is analyzed for uniform linear array and planar array antenna structures, focusing on beamforming and beam-steering techniques. [39] addresses the challenge of uplink coverage enhancement in sub-6 GHz 5G NR systems using adaptive digital beamforming with cross-polarized array antennas. They propose an adaptive beamforming approach based on cross-polarized array antennas and analyze the performance in improving uplink coverage near the cell edge. The study emphasizes the importance of uplink beamforming for achieving optimal downlink beamforming performance in time division duplex (TDD) mode. In [40], energy-efficient 5G mm-wave cellular networks with beamforming capabilities are examined. Comparing various beamforming architectures to a 4G reference network, the study demonstrates that 5G networks, under the same coverage performance, require more base stations but with significantly improved energy efficiency.

[41] explores massive multiple-input multiple-output (MIMO) technologies for 5G evolution (5GE) and 6G networks. The paper highlights the role of advanced beamforming technologies and massive MIMO combined with base station cooperation in achieving stable, high-data-rate mm-wave transmission. Experimental results and link-level simulations demonstrate the potential of massive MIMO technologies for 5GE and 6G, including over 100 Gbps downlink throughput and coverage performance in sub-terahertz frequency bands. A wideband phased array antenna with wide-angle scanning capability for mobile communication systems is proposed in [42]. Their approach involves embedding an air cavity beneath each array element, improving wide-angle scanning impedance matching, and extending the operating bandwidth. The study presents experimental results for linear and planar array prototypes, demonstrating wide-angle scanning coverage and high realized gain within the bandwidth.

The studies discussed in this review explore new architectural designs, low-cost reflect-array solutions, advanced beamforming techniques, energy efficiency considerations, and the application of massive MIMO technologies. These advancements contribute to the evolution of 5G networks and pave the way for 6G systems with higher data rates, broader coverage, and improved performance in various communication scenarios.

2.4.3 Phased Array Antennas

Phased array antennas have not only transformed satellite communications but have also found extensive applications in various other fields. In addition to satellite communications, phased arrays have been widely adopted in radar systems, wireless networks, and even automotive radar systems. Electronic steering of the beams without mechanical movement provides various advantages, such as faster response time, increased agility, and enhanced performance.

In radar systems, phased array antennas enable beam scanning in multiple directions, allowing for detecting and tracking targets with high accuracy and efficiency. Phased arrays offer fast scanning capabilities by electronically steering the beams, crucial in applications such as air traffic control, weather monitoring, and military surveillance. Moreover, they have been critical in advancing wireless communication networks, particularly in deploying 5G and beyond. The dynamic beamforming capabilities of phased arrays enable the optimization of signal strength, interference mitigation, and improved capacity. By adaptively steering the beams toward desired user locations, phased arrays enhance coverage, reduce signal degradation, and support higher data rates, enhancing user experience. Furthermore, the automotive industry has embraced phased array antennas for collision avoidance systems and autonomous driving. Vehicles can accurately detect and track objects in real time by employing phased arrays, enabling advanced driver assistance and enhancing safety.

Phased array antennas have revolutionized various industries by providing electronically steerable beams. Their dynamic beamforming capabilities offer numerous advantages, including rapid beam steering, improved coverage, increased capacity, and enhanced performance. From satellite communications to radar systems and wireless networks, phased arrays have become a critical technology pushing modern communication systems' boundaries.

2.4.4 Antenna Types Used in Phased Array Design

Phased array antennas consist of an array of individual radiating elements, and selecting the antenna element type is crucial for achieving the desired performance and beamforming capabilities. Different antenna types are commonly used in phased array designs:

a) **Patch Antennas:** Patch antennas, also known as microstrip antennas, are commonly used in phased array designs due to their compact size, low profile, and ease of integration with integrated circuits.
b) **Dipole Antennas:** Dipole antennas are one of the fundamental antenna types used in phased array designs, offering omnidirectional radiation patterns and simplicity in fabrication.
c) **Horn Antennas:** Horn antennas find applications in phased array systems operating at microwave and millimeter-wave frequencies, providing low sidelobe levels with high gain and directivity.

d) **Slot Antennas:** Slot antennas are popular for phased array designs at higher frequencies, offering low profile, wide bandwidth, and sound radiation characteristics.

The choice of antenna type depends on various factors, including the desired frequency range, beamwidth, gain, and system requirements. Each antenna type has advantages and limitations, and careful consideration must be given to the specific application in phased array design.

2.4.5 Beamforming

Beamforming is the cornerstone of phased array antennas, enabling precise control over the directionality and spatial characteristics of the antenna's radiated beam. By appropriately adjusting the phase and amplitude of the individual elements, beamforming facilitates the creation of focused beams, enhancing signal strength and reducing interference. The main types of beamforming methods include analog and digital beamforming, each with advantages and limitations.

Analog beamforming operates at the radio frequency (RF) level and utilizes phase shifters to adjust the phase of the signals in the analog domain. This technique is commonly employed in phased arrays with many elements. Analog beamforming provides a simple and low-latency solution suitable for applications with relatively static channel conditions. However, it may have limitations in adapting to dynamic environments or supporting advanced signal processing capabilities. On the contrary, digital beamforming operates in the digital domain, where the signals from each array element are individually digitized and processed. Digital beamforming provides more flexibility and adaptability, allowing for advanced signal processing algorithms, such as adaptive beamforming and interference cancellation. This technique is particularly advantageous in rapidly changing channel conditions, as it can dynamically adjust the beamforming weights to optimize performance. However, digital beamforming generally requires more complex hardware and higher computational resources. Both analog and digital beamforming techniques have advantages and limitations, and their choice depends on the application requirements. Analog beamforming is often favored for its simplicity and lower implementation complexity, while digital beamforming offers greater flexibility and adaptability in challenging environments. Selecting the appropriate beamforming technique is a trade-off between performance, cost, and system constraints.

Hybrid beamforming is a more sophisticated method that combines the benefits of both analog and digital beamforming approaches. It addresses the trade-off between performance and complexity by combining analog and digital processing stages in the beamforming network. In hybrid beamforming, the phased array antenna system is divided into multiple sub-arrays, each consisting of smaller elements. The analog beamforming stage is employed at the sub-array level, where analog phase shifters control the phase of the signals, enabling beam steering and shaping at a coarse level, reducing the number of required RF chains, and simplifying the hardware implementation. The outputs of the sub-array analog beamformers are then fed into digital beamformers, where further signal processing is performed at the digital stage. The digital beamformers refine the beamforming weights and adjust the phase and amplitude of the signals with higher granularity, allowing for more precise control of the beams, adaptive beamforming, and interference cancellation.

In summary, beamforming techniques, including analog and digital beamforming, are essential for achieving precise control and optimization of the radiated beam in phased array antennas. These techniques are critical in improving signal quality, enhancing coverage, mitigating interference, and providing efficient communication in various applications ranging from wireless networks and satellite communications to radar systems and medical imaging.

2.4.6 Use of Beamforming for Improved Capacity and Coverage in Non-Terrestrial Networks

NTN satellite communication systems require efficient resource allocation to meet the growing demand for high-speed and reliable communications. Beamforming is critical in improving capacity and coverage in NTN by:

a) **Overcoming Path Loss:** Beamforming allows for dynamic beam shaping and direction adaptation, mitigating the adverse effects of path loss due to long propagation distances. Rain fading can also be mitigated by focusing the beam on the desired areas, improving system reliability.
b) **Obtaining Multi-Beam Coverage:** Beamforming enables the generation of multiple beams that can be steered independently to serve different regions or user groups simultaneously. The multi-beam coverage capability optimizes satellite resources and ensures efficient coverage across different areas.
c) **Managing Interference:** Beamforming facilitates identifying and tracking interfering signals, allowing adaptive nulling or beam steering to mitigate interference. This interference management capability is crucial in NTN, where co-channel interference can significantly impact system performance with multiple satellites and users.

2.4.1 Conclusion

Phased array antennas and beamforming techniques are vital enablers that improve the capacity and coverage of satellite links in non-terrestrial networks. These technologies enhance signal strength, increase system capacity, and mitigate interference by exploiting dynamic beamforming capabilities. This overview highlights the research and advancements in the field, providing a foundation for further exploration of beamforming and phased array antennas in satellite communication systems.

2.5 Challenges and future directions

Achieving global coverage of communication networks is only possible with satellite-based support of terrestrial networks. Mega-constellations in LEO are promising to meet the requirements of the next generation of communication. A key component of a communication satellite is the antenna. Future satellite antenna systems have to generate beams with high gain, low sidelobes, low cross-polarization, high beam efficiency, wide scanning range, and beam steering and shaping capabilities [25]. This subsection summarizes the dominant trends and challenges of satellite-based antennas. The mentioned trends and challenges are not complete, more examples can be found in the references [25],[43]-[47].

The general trends in the development of satellite antennas are toward highly integrated solutions at higher frequencies, higher bandwidths, higher power levels, higher gains, and larger aperture dimensions. Further, antennas have to be large (area-wise), lightweight and deployable [25]. Addressing all of them simultaneously is difficult, but necessary to enable global satellite communication networks. Not only from the electrical and mechanical point of view, future antenna solutions have also to be feasible from the economical point of view. Providing low-cost and high-performance antennas are essential to reduce overall payload costs and facilitate investments into non-terrestrial networks (NTN).

Depending on the constellation distinctions has to be made between antennas for LEO, MEO, and GEO services since the boundary conditions differ. For communicating with GEO satellites, very large distances have to be overcome. Otherwise, with LEO satellites, these are much smaller, but new challenges arise, for instance, beam following and user-handovers. Consequently, also the requirements for the antennas are different and the challenges and trends vary [25].

For fixed satellite services and broadcast satellite services in GEO or MEO orbits, contoured beam antennas and multi-beam antennas are of interest. Contoured beam antennas allow adjusting of the beam to optimize the use of power in the covered region. While multi-beam antennas use a large number of spot beams to cover the geographic coverage region by dividing the frequency spectrum into sub-bands, which can then be reused, and the effective bandwidth, and thus capacity increased [25],[43].

While for services in LEO orbits smaller propagation distances reduces the requirements for higher gains. However, LEO satellite services require antenna radiation patterns that cover a wide scan range and allow precise electronic beam steering and beamforming. Large flat-panel active phased array antennas that incorporate electronic components such as filters, power amplifiers, low noise amplifiers, and beam steering electronics can achieve low-cost, small, and efficient radio frequency front ends [25].

Another trend is the usage of dual-band or even multi-band antennas allowing, on the one hand, redundancy, and on the other hand, parallel service integration, for instance, dual usage of L-band and S-band with a single antenna [25],[43].

Reconfigurable antennas are also of rising interest since the onboard flexibility allows the operator to adjust quickly to the market needs. Finding a compromise between reconfigurability, costs, and risk is challenging [44].

Summarized, many challenges have to be solved to enable satellite-based communication, especially for new LEO NTN constellations. To repeat a few, using higher frequency bands, wide scan widths with accurate electronic beam steering, and low weight and size while providing an area-wise large shape. Besides electrical and mechanical improvements, the costs also have to be reduced significantly.

2.6 Additive Manufacturing Techniques for Antenna Development

2.6.1 Introduction

Once the design and simulations of any electromagnetic component have been completed, it is necessary to validate the prototype from the results obtained with real measurements. Additive Manufacturing (AM) is the suitable technology for this purpose. The main advantage of using this printing technique is the ability to manufacture lightweight components with complex internal surfaces in a single object. On the other hand, one of the main disadvantages is the manufacturing precision as well as the surface roughness, which show worse performances compared to standard manufacturing processes, and mainly dependent on the type of material and process parameters [48].

2.6.2 Stereolithography (SLA)

In this context, 3D printing technology may represent the best solution from a manufacturing point of view thanks to the possibility of integrating different electromagnetic elements into a single part. On the one hand, stereolithography (SLA) is a photopolymerization process based on the use of an ultraviolet laser to solidify a liquid resin. In this case, as it is a liquid process, support structures are necessary during the manufacturing phase [49]. The process is divided into layers, where the coating is smoothed by a recoater and cured with a UV laser. The platform is then lowered to complete the process layer by layer until the manufacturing process is finished [50]. The process continues through a UV oven where the formed part is placed for curing because, during solidification, the photopolymer shrinks and can cause curvatures and distortions.

This method makes it possible to produce parts with high precision and very little surface roughness. However, plating the internal surfaces can be critical in terms of adhesion, uniformity and stability, which would limit RF applications in space [51].

2.6.3 Selective Laser Melting (SLM)

On the other hand, in the frame of the radiating element, Selective Laser Melting (SLM) is probably the most suitable process because all parts are printed in metal. This process consists on a selective fusion of bed of metal powder (spread by a recoater in the building platform) to realize, step by step, the desired part. At the end of the process, the powder not fused is removed and the part is still attached to the building platform. Subsequently, a stress-relieving job is carried out in an oven to reduce residual stress that would lead to undesired deformations. Finally, the components are separated from the building platform and eventually subjected to surface finish treatment as polishing and shot peening [52]. The properties of the metal powder are important in both the quality and cost of the part. The main characteristics that influence the process are geometrical, such as size and shape; metallurgical, such as composition; and physical, such as fluidity or light absorption [53]-[55].

The main advantage of using this AM process for RF applications is that it can offer directly printed parts in aluminum alloys such as AlSi10Mg, AlSi7Mg, and Scalmalloy [56], with optimal dimensional accuracy and electrical properties [57].

2.6.4 AM-Oriented design approach

Extremely important steps in the SLM process are the orientation of the part in the building platform and the design of the supporting structures. A possible solution to reduce the number of supports is to choose an optimal building orientation of the structure [48]. It should be noted that the staircase effect must also be considered for specific applications [58]. Another important aspect to consider are the protruding surfaces. These surfaces are areas not supported by solidified material during the building process. The heat conduction rate of the powder-supported areas is lower than that of the solid-supported areas, while the absorbed energy is higher. The melt pool created by the laser becomes too large and sinks into the powder. Therefore, deformation occurs if these surfaces are not supported. However, higher manufacturing accuracy has been observed in literature for components designed with an *AM-oriented approach*.

Manufacturing components using AM processes is complicated in several ways. One of them is considering that internal post-processing such as metallization in SLA or powder removal in SLM has to be carried out. A simple strategy is to split the component into two or more parts in order to handle the post-processing. However, a new drawback is the misalignment of the different parts, leading to leakage and thus to higher losses. This is why the result is inefficient [48].

Therefore, the designed part must be made monolithically in order to take full advantage of the AM process. To this end, the design must be adapted to the *AM-oriented design approach*, where the most important point is to align the propagation axis with the direction of construction, avoiding the presence of overhanging structure in internal cavities. In this way, higher manufacturing accuracy and cross-sectional symmetry is achieved, which is essential for dual-polarized components [48].

2.7 Integrated filtering antenna array solutions for satellite communications

The rising interest in new SATCOM constellations demands the miniaturization of satellite communication (SATCOM) payloads which in turn requires minimization of the mass, volume, and power consumption of spacecraft and launches. A LEO SATCOM payload heavily relies on RF front-end architecture, which depends on antenna configurations and beamforming techniques [59]-[61]. The RF front-end architecture becomes extensively complex and cumbersome with the increasing needs of the user needs. Integrated solutions for next-generation satellite constellations and ground terminals pave the way for meeting the requirements of power, size, and processing speed limitations. Additionally, the filter-antenna integrated solutions using various synthesis approaches improve frequency selectivity, quality factors, out-of-band suppression, stability in in-band gain, and efficiency [62].

2.7.1 Integrated Filtering Antenna Array Solutions

The RF front end comprises a transmitting and receiving antenna integrated with filters, collectively known as filtering antennas [63]. Conventionally, passive electrical components such as filters, duplexers, and antennas are designed and manufactured separately and then cascaded. Integrated multifunctional frontends provide a highly effective solution that enables low-cost, power-efficient, and miniaturized wireless systems [64].

2.7.2 State-of-the-art Design Methods

Filtering antennas can be designed using three typical methods: cascaded, synthesis, and fusion-based approaches. In the traditional cascaded method, filters and antennas are designed separately and then combined using a 50-ohm interface to select the desired signal and suppress undesired out-of-band interference. The synthesis method utilizes the antenna's radiating element as the last resonator of the Bandpass Filter (BPF). Fusion methods, on the other hand, employ a novel approach to designing a filtering method without the need for additional filtering circuits [63].

2.7.3 State-of-the-art designs

Previously, several scholars proposed various integrated filtering antenna solutions. Of the many, some of which are presented and discussed below. Of the many, some of which are presented and discussed below. The designs can be categorized as those adopting a direct integration [65]-[68], [71], Synthesis based [69],[72], and Fusion based [70], [73]-[75]. Besides, some are linearly polarized (LP) [65]-[72],[74], while very few are circularly polarized (CP) [73],[75]. The filter function varied from BPF [71]-[72], Harmonic/band suppression [65]-[66],[68]-[69],[71],[74]-[75], Frequency selective [70],[73], and dual-band [67], [75].

[Ref.]	Frequency (GHz)	Integration Method	Function	Integration Structure	Antenna Dimensions (mm)	Circular Polarization	Gain
[65]	11,575	Direct Integration	harmonic suppression	Defected ground structure	34 × 16 × 1.6	No	6.14
[66]	11,79 - 13,05	Direct Integration	Stopband Suppression	stepped metal rod	-	No	15
[67]	18,4 - 19,5	Direct Integration	Dual-band	Defected ground structure	38 × 6.6 × 4.5	No	-
[68]	12.25 –12.7	Direct Integration	Out-of-band rejection	Radiating slots	123 × 19.05 × 9,525	No	16
[69]	10.6 - 10.8	Synthesis Method	Band Isolation	SIW	22.1 × 19.7	No	-
[70]	9,7 - 10,5	Fusion	Frequency Selective Filter	Multi Layered Structure	12 × 12	No	-
[71]	12,1 - 12,8	Direct Integration	BPF and Band rejection	Slot Resonators	60 × 16 × 5.5	No	13.6
[72]	17 - 23,6	Synthesis Method	BPF	Pedestal	26 × 26 × 45.6	No	13.8
[73]	30	Fusion	Frequency Selective Filter	SIW	6 x 6 x 3.2	Yes	13
[74]	12-12,75	Fusion	Band suppression	Slot resonators	19 x 14,575	No	14,45
[75]	17,7-21,2	Fusion	Dual-band with high suppression	Multi Layered Structure	60 x 10,25	Yes	22

2.7.4 Future Directions

While characteristic mode analysis has traditionally been used to design and analyze modal current distribution and the radiation capabilities of electromagnetic structures, recent research has explored its application as a tool for controlling antenna modes. This allows for the suppression of undesired modes and the excitation of desired in-band modes based on modal current distributions. Active research is currently focused on achieving filtering characteristics by utilizing characteristic mode analysis. Unlike the other design methods discussed earlier, this approach achieves the desired filtering response solely by manipulating antenna modes, without the need for additional filtering structures. This method has shown promising results, including reduced insertion losses, a radiation efficiency of approximately 95%, and out-of-band suppression levels exceeding 27 dB, all without additional filtering circuits [76]-[77]. Throughout this project, this method, along with other briefly discussed methods, will be explored to determine the best-integrated filtering antenna array solutions for satellite communication applications.

2.8 Dual-Band mm-Wave Phased Arrays for LEO SatCom Broadband User Terminals

The past decade has witnessed the development and launch of LEO satellite constellations. While there has been significant effort in building user terminals that are either mechanically steered or combine electronic and mechanical steering [61], phased arrays have emerged as a viable solution for the implementation of SATCOM terminals since the development of suitable Si multichannel beamformer chips [78]. Phased array terminals offer near-instantaneous steering and can be low profile, a key requirement for SATCOM-on-the-move applications.

Phased array terminals typically use separate transmitter (Tx) and receiver (Rx) array apertures. Therefore, the cost and footprint are doubled, spurring efforts towards the development of shared aperture, dual band phased array terminals that can cover both the K and the Ka bands. Since the SATCOM industry is fragmented among different operators, there is also a need for terminals that can cover the whole K and Ka bands, as well as the different polarizations and scanning angles. The targeted frequency bands and polarizations are given in table 2.8.1 [79].

Frequency bands (GHz)	17.7-21.2 (Tx) 27.5-31 (Rx)
Polarization	RHCP/LHCP

Table 2.8.1: Frequency bands and polarization requirements for K-Ka band SATCOM user terminals

Several publications concerning the development of suitable arrays have emerged, but they either face manufacturing issues or problems realizing the required bandwidth, steering angles, and isolating the Rx and Tx. A collection of such publications is given in table 2.8.2. Some make use of an interleaved lattice, resulting in arrays that are optimally sampled (for non-radiating grating lobes) for both bands, thus avoiding the increasing costs and integration density that are an inherent issue for arrays using wideband elements to cover both the Rx and Tx bands. However, they still face challenges related to achieving the required bandwidth, scanning angles, polarization, and face manufacturing challenges. An additional challenge is the isolation between the Rx and the Tx, that is vital for full-duplex terminals.

Reference	**Frequency bands (GHz)**	**Scan range**	**Element type**	**Polarization**	**Isolation (dB)**	**Comments**
[80]	20.2-21.2 29.5-30.8	± 50°	Via cavities	Linear	-25	Separate Tx and Rx ports
[75]	17.7-21.2 27.5-31.0	± 60°	Substrate integrated waveguide	RHCP LHCP	-40	Vertical PCBs
[81]	19.7-20.2 29.5-30	± 55°	Patch	RHCP LHCP	-	Use of polarizer
[82]	18-30	± 60°	Vivaldi	Dual linear	-12	Poor xpol isolation
[83]	18-41	± 45°	Tightly Coupled Dipoles	Linear	-	

3 HAP Antennas

3.1 Introduction to HAPs and their role in non-terrestrial networks

High Altitude Platforms (HAPs) are airborne systems that operate at altitudes between 20 to 50 kilometres above the Earth's surface [84]. They typically consist of unmanned aerial vehicles (UAVs), airships, or balloons that are stationed in the stratosphere. HAPs have gained significant attention in recent years due to their potential role in non-terrestrial networks and their ability to provide various services. Compared with existing network infrastructure, HAPS has a much larger coverage area than terrestrial base stations and is much closer than satellites to the ground users.

According to the findings presented in [85], in addition to small cells and macro-cells, High Altitude Platforms (HAPs) have the potential to provide a unique mega-cell concept that can complement existing networks in future wireless systems such as 6G and beyond. This research paper thoroughly explores the potential use cases of integrating HAPs into existing legacy networks. In particular, the works presented in [86] and [87] focus on studying the integration of HAPs with terrestrial networks, while [88] examines the integration with satellite networks to enhance overall network performance. By investigating the integration of HAPs into both terrestrial and satellite networks, these studies shed light on the challenges that arise when incorporating HAPs into existing infrastructure. The research aims to identify and understand the obstacles and complexities associated with HAP integration, providing valuable insights for the development of efficient and effective integration strategies. By addressing these challenges and understanding the potential benefits of integrating HAPs, such as extended coverage, improved network performance, and enhanced user experience, this research paper contributes to the ongoing efforts in leveraging HAP technology for the advancement of non-terrestrial networks.

The work in [89] explores the potential benefits of integrating HAPs mounted Small Base Stations (SBSs) into terrestrial Radio Access Networks (RANs) to support energy and resource allocation strategies in future 6G networks. The focus is on leveraging the capacity of HAPs to offload a limited portion of terrestrial traffic, thereby allowing for the deactivation of low-loaded Base Stations (BSs) during off-peak periods and enabling sustainability in future networks. While the offloaded fraction may not meet the entire bandwidth demand of future networks, it offers an opportunity to save energy and pursue sustainability goals. The study prioritizes delay-tolerant traffic for offloading to the aerial SBSs to ensure the preservation of Quality of Service (QoS) for delay-sensitive services. Additionally, the research investigates the flexible allocation of HAPS bandwidth, enabling its targeted deployment in specific areas or redirection to areas where it can effectively improve energy efficiency and reduce the reliance on ground-based energy supply.

The author of [90] presented two architecture designs for HAPS systems: repeater-based HAPS and BS-based HAPS. Both designs are considered viable technical solutions. The energy efficiency of the two architectures is analyzed and compared using consumption factor theory. The performance of the systems is evaluated through Monte Carlo simulations, with a focus on spectral efficiency metrics using LTE band 1 for single-cell and multi-cell scenarios. Both designs demonstrate favorable downlink spectral efficiency and coverage.

Furthermore, HAPs can act as relays or aerial BSs, facilitating communication between ground-based systems and satellites. By acting as intermediaries, HAPs can improve the efficiency and reliability of wireless communication links, especially in scenarios where direct communication between ground-based stations and satellites may be challenging or costly. The deployment and operation of HAPs in non-terrestrial networks, however, present unique challenges. These include issues related to regulatory frameworks, airspace management, power supply, communication protocols, and network management. Additionally, the design and implementation of HAPs require considerations such as platform stability, long endurance, payload capacity, and resilience to adverse weather conditions.

Overall, HAPs offer a promising solution for extending network coverage, improving communication links, and enabling various services in non-terrestrial environments. Ongoing research and development efforts aim to address the technical and operational challenges associated with HAPs, paving the way for their integration into future communication networks.

3.2 Antenna requirements for HAP-based communication systems

The antennas used in HAP communication systems are highly directional, which is required to support long link lengths and high data rates intended for broadband communications. The major design aspects considered for HAP antennas are:

1. Number of cells: The coverage area of an HAP system is divided into multiple sub-areas known as cells. Each HAP antenna illuminates one cell. When each cell is serviced by one antenna, the antenna aperture increases with increase in the number of cells in a fixed service area. The antenna aperture roughly obeys an N^2 relationship, where N is the number of cells [84].
2. Radiation pattern: The main lobe patterns of aperture antennas approximately follow a $\cos^n \theta$ relationship, where θ is the angle from antenna boresight, and *n* is chosen for a required beamwidth and side lobe floor [91]. The signal strength at the cell's perimeter should be comparable to that at the cell's center. At the same time, the power roll-off must be significant in order to avoid interference with the adjoining cells. Figure3. 1 shows a comparison of the main lobe curves. In order to get comparable power at the cell edge and the center, the 3 dB antenna beamwidth is a good option, however, due to the low power roll-off, the interference with the adjacent cells may be high. On the other hand, the 10 dB curve would result in lesser interference, with a degraded performance at the cell edge. The decision for the desired pattern would be a trade-off between improving the power delivered at the cell edge and minimizing interference with adjacent cells. In [92], it is shown that for an aperture antenna used in HAP, the optimum half-power beamwidth (HPBW) should be ≈ 0.837 of the angle subtended by the cell on the ground, which gives a 4.3 dB roll-off at the cell edge.

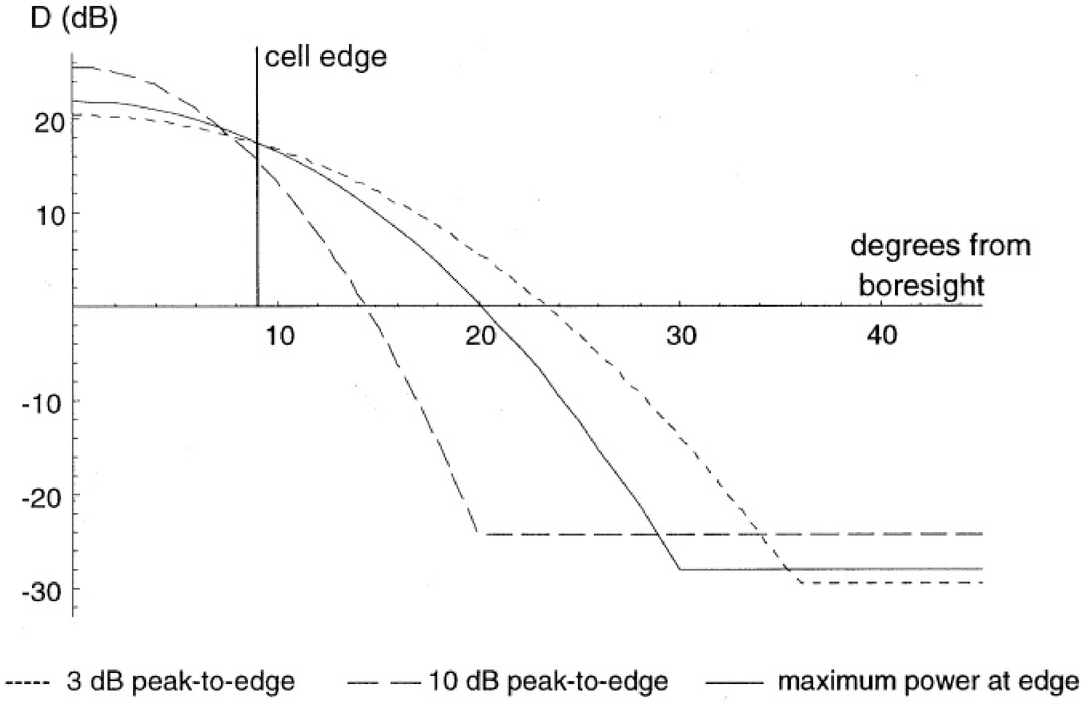


Figure3. 1: Comparison of main lobe curves ***Error! Reference source not found.***

3. Antenna directivity: The antennas implemented in HAPs would be operated in the stratosphere (17-22 km) [93] and deliver services in their designated areas. Hence the required directivity would have to be high. The maximum directivity for aperture antennas used in this application can be approximately given by [94]:

$$D_{max} = \frac{32 \log 2}{\theta_{3dB}^2 + \phi_{3dB}^2}$$

where θ_{3dB}^2 and ϕ_{3dB}^2 are the 3 dB beamwidths in two orthogonal planes.

Using circular beam patterns for HAP antennas often results in an elliptical footprint at low elevation angles, as shown in Figure 3.2. Employing an antenna with an elliptical beam pattern compensates this problem, as shown in [92], where the exact expressions for the directivity and cochannel interference are also derived.

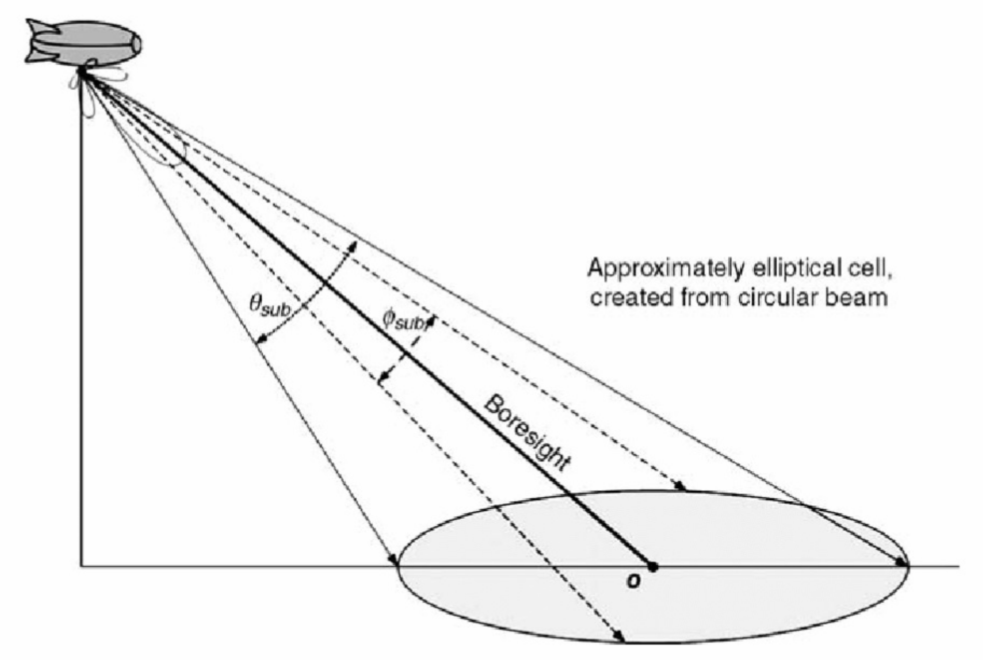


Figure 3.2: Elliptical footprint due to circular beam pattern ***Error! Reference source not found.***

4. Beam steering: HAPs often have the tendency to get vertically, or horizontally displaced from their designated positions in the atmosphere. Figure 3.3.3 shows the effect of this displacement on the service area.

The antenna beam steering mechanism must be chosen such that the cochannel interference and directivity at cell edge are not significantly affected. The following two conditions apply:

- The antenna payload must accommodate mechanical steering, in order to compensate the effect of HAP displacement.
- Handover to other channels should be supported by both HAP and user terminals.

In [91], beam steering solutions following these conditions are described in detail.

Along with these listed requirements, HAP antennas should also have a high radiation efficiency, lightweight and compact design, and be designed for operation over a wide frequency range.

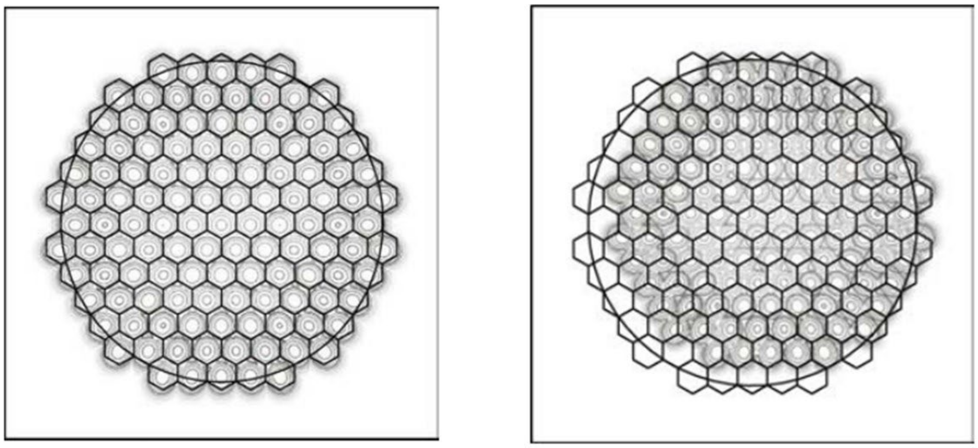


Figure 3.3: Effect of HAP displacement on service area ***Error! Reference source not found.****. Left image shows the HAP providing coverage over the service area. Right image shows the situation of displaced HAP, leading to loss of coverage in some of the cells.*

3.3 Novel antenna designs for HAPs, including planar and conformal arrays

Previous antenna designs for HAPs have mostly focused on using relatively simple technologies to achieve multiple fixed beams from a single platform. This way, HAPs can make use of their high altitude to generate several cells that cover huge swaths of terrain. Examples of such antennas include single-feed-per-beam waveguide antennas [95] and fixed beamforming analogical phased arrays [96].

The main limitation of fix-beam HAP antennas is straightforward: they are unable to steer the beams to keep providing service in case the location of user clusters changes. However, if the goal of a HAP in particular is to serve a fix area on the ground, this might not be an issue. Another, more fundamental issue of HAPs that novel antenna designs need to compensate for is cell drift. Over time, footprints on the ground may shift in several ways, due to the air currents that HAPs are subjected to owing to stratospheric winds and turbulence. Even though, normally, average position can be controlled relatively accurately, rapid short-term instabilities can cause footprint shift in several ways. This results in an increase in handovers, disconnections, and overall lower QoS for users [97]. Steerable beamforming would allow HAPs to counter this problem, as Figure3.44 shows.

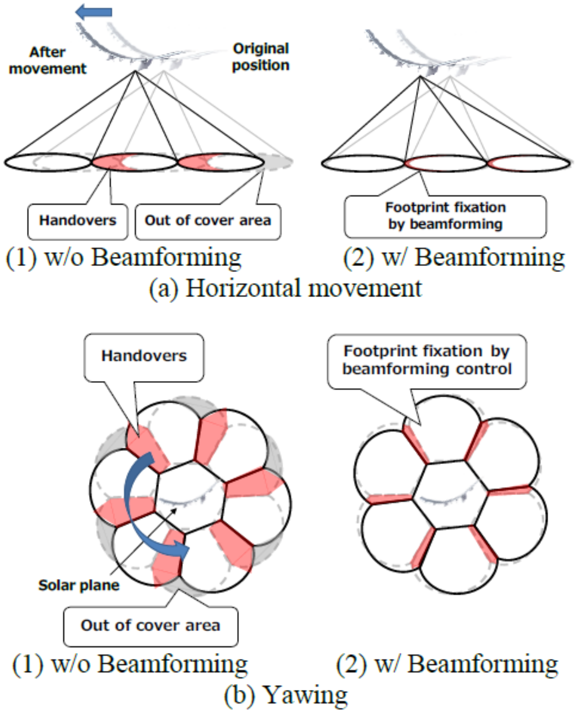
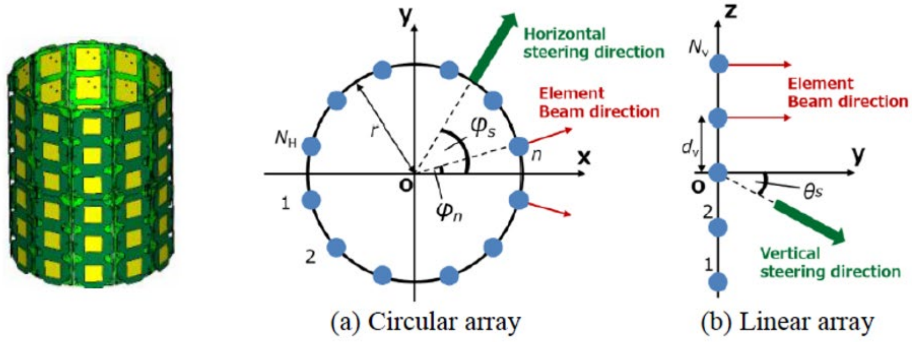


Figure3.4. Footprint shifting due to aircraft movement and beamforming correction. [3]

Theoretically, a parabolic antenna with a mechanical gimbal pointing system could be employed for both of these problems. Nevertheless, this solutions does not have multiple beam capabilities, its beamsteering speed is limited, and it presents a mechanical point of failure. In fact, Project Loon (from Google's subsidiary company X), which employed three mechanically steered Cassegrain reflectors, was terminated in January 2021. Even though the main reasons behind the decision were economical in nature, the released technical files also highlight some key limitations of the employed antenna approach [98].

In order to address both issues in a more effective way, past literature has looked into electronically scanned arrays. While some of them are classical planar arrays [99], [100], others adopt a conformal approach. One example is the antenna developed by SoftBank and HAPSMobile [101], a patch conformal array in the shape of a vertical cylinder. This allows for control over horizontal beam steering by use of circular arrays in the horizontal plane, and also enables vertical beam steering via planar arrays in the vertical plane. Figure 3.5 highlights this structure. Figure 3.6 shows the developed prototype.



(a) Circular array
(b) Linear array

Figure 3.5. Cylindrical array antenna structure [6].

Figure 3.6. HAPS Mobile and SoftBank antenna prototype [6].

An additional advantage of the vertical cylinder shape is coverage. A regular, downward-facing planar array may have its coverage (i.e. terrain covered around the HAP) limited by the maximum steering angle. This is not the case for side-facing radiating elements of the cylinder, allowing this antenna to have a much higher coverage range. Admittedly, such antennas cannot effectively serve the area immediately below them, but the addition of an inexpensive fix-beam antenna at the bottom of the HAP is sufficient to generate the desired footprint.

Another HAP conformal array antenna shape that has been studied consists of dual concentric conical arrays [102]. This shape reduces secondary lobe and back lobe levels: compared to a dual circular array, the secondary major lobe decreases by 13 dB, all the way down to -40 dB relative to the main lobe. One additional advantage is aerodynamics. A conical shape is much more adapted to be included in a fuselage than the vertical cylinder discussed above, while still presenting better performance in near-perpendicular scanning angles than a regular planar array, resulting in a higher coverage range.

Moving onto a different topic, a key advantage offered by antenna arrays compared to fix-beam antennas is the possibility of using MIMO technologies. With HAPs being an essential driving force behind the extension of coverage and throughput in 6G, it is important that they possess MIMO capabilities to aid in this task. HAP MIMO systems using both planar [103] and conformal [104] exist in the literature. Interestingly, cylindrical phased arrays in HAPs can achieve 2.1 times the capacity of regular planar array

MIMO systems, as well as a Signal-to-Interference-plus-Noise ratio (SINR) that is 10 dB higher at the edge of the beam footprints [104].

Finally, one important aspect to point out is user terminals linking the HAP to the ground. In some cases, the system might be direct-to-mobile phone. However, other use cases might target higher frequencies where handheld devices do not operate, or higher throughput by use of directive antennas in a ground station. In those cases, a combination of mechanical and phased array steering can be an effective combination to achieve lower cost and higher performance than a fully mechanical or fully electrical alternative [105]. Mechanical points of failure are much less of a concern now that the equipment is on the ground and can easily be maintained and repaired.

3.4 Integration of HAP antennas with other technologies

Figure 3.7 shows an integrated Vertical Hetrogeneous Network (VHetNet) envisioned for 6G, with an implementation of HAP station (HAPS) with low earth orbiting (LEO) satellites, unmanned aerial vehicles (UAV) and terrestrial network.

- The HAPS would provide high speed and efficient connectivity between LEO satellites, eliminating the requirement for ground stations for inter-satellite communications [106]. Moreover, the probability of collisions between satellites would also be calculated by the HAPS, along with acting as a data center for recording satellite trajectory.
- The mobility of UAVs would be governed by the HAPS. Offloading heavy computations and handling large-scale sensing and monitoring would also be some of the functions of the HAPS [107].
- The HAPS layer would enable the provision of fast internet access and wireless communication services to densely inhabited and remote places without relying heavily on satellite networks.

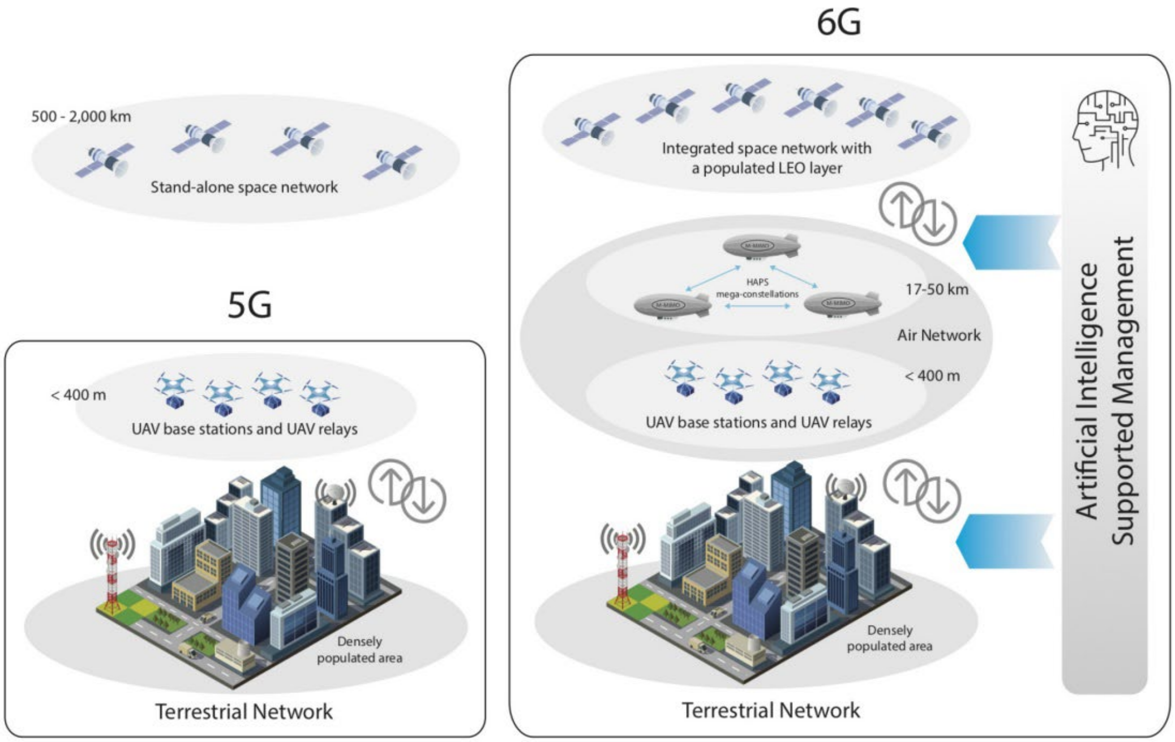


Figure 3.7: Transition from 5G to 6G ***Error! Reference source not found.***

4 Drone-Based Antennas

4.1 Use of UAVs for non-terrestrial communication

UAV are flying aircraft controlled without human crew onboard but are rather controlled remotely or autonomously [108]. UAVs offer a cheap, quick, flexible and solution compared to satellites which are generally meant for long temp deployment. Furthermore, UAV can be deployed for operation within hours while satellites require months to years [109]. This makes UAVs suitable for rapid deployment in environment with dynamic demand for wireless communications. Although satellites offer a much higher area coverage in contrast with UAVs which only offer relatively low area coverage. But the operation cost of UAVs is significantly lower than satellites for initial deployment as well as replacement due to equipment failures is much faster and cheaper than satellites. Thus, for a well working NTN network with maximum adaptability and cost-efficiency, UAVs are involved as well to be able to respond to dynamic environment such as natural or man-made disaster-stricken areas which only require temporary network deployment until its original network is replaced and usage of satellite is not possible or too costly. Thus UAVs are an essential part of a NTN network.

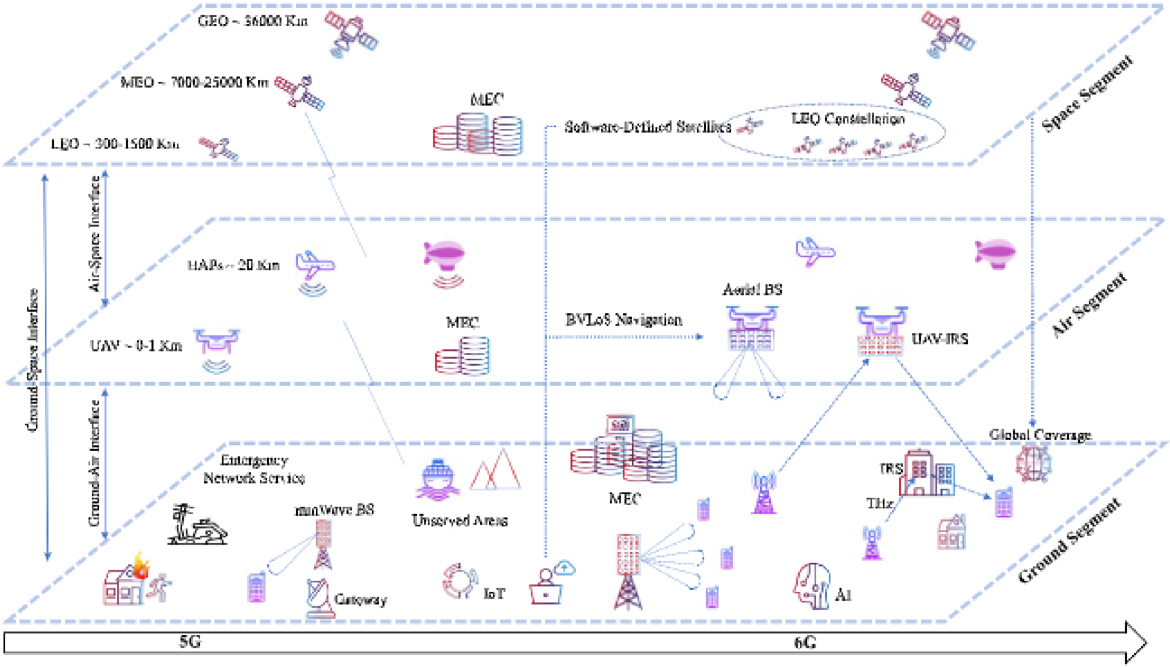


Figure 4.4, Visualization of NTN network through co-operation of satellites and UAVs[2]

4.2 Antenna design challenges and considerations for drone-based networks

4.2.1 Introduction

As can be expected, the use of UAVs has increased over the last few years. Their applications range from civilian applications such as topography, video streaming and others; to military applications such as surveillance, rescue, and target location. These applications require several links for communications including telemetry, telecommand, GPS, etc. [110].

On the other hand, if we talk about non-terrestrial networks, the UAV is a great candidate to be considered as an air base station, within the limitations and capabilities that can be offered from this aircraft, in order to complement both the coverage and the capacity of conventional terrestrial networks [111].

4.2.2 Chanllenges and considerations

Regarding antenna design, the following considerations should be taken into account:

- ***Frequency band:*** UAVs need to transmit mission information and sensory data such as high-resolution images in real time. Therefore, high data rates will be required. Starting from the microwave bands widely used in conventional terrestrial networks, proper deployment may not be possible due to the scarcity of spectrum in the sub-6 GHz band and its severe interference. This is why millimeter waves are strong candidates for non-terrestrial links in new generations of mobile networks such as 6G, being able to offer greater resources, thus guaranteeing high-speed transmission [112].

- ***Dimensions*:** as physical properties, such an antenna should be small in size and lightweight, as it should not affect the aerodynamic properties of the vehicle itself, as well as the power and battery management [113],[114].

- ***Radiation pattern:*** when an antenna is designed, the radiation pattern of the cell is a crucial factor influencing the performance of the system [115]. Antennas currently implemented in terrestrial base stations have a certain tilt to serve terrestrial users. However, an airborne base station such as a UAV may be at higher altitudes, significantly losing antenna gain. In addition, the UAV must provide communications services efficiently and fairly to both terrestrial users and other receivers that are inaccessible to the ground base station.

- ***Directivity*:** In terms of antenna design, to compensate for millimeter wave propagation attenuation due to high frequency and long transmission distance, highly directive cells should be considered [116]. Compared to the use of conventional millimeter band directive antennas (horn antennas, reflector antennas and lens antennas), the use of integrated antennas, whose advantages are their small size, lightweight, low cost of materials and ease of manufacture, prove to be suitable for UAV communications due to their physical limitations.

- ***Cell array*:** the antenna array will play an important role due to the advantages offered by the grouping of radiation cells. This will provide high directional gain as well as beamforming capabilities.

4.2.3 *Proposed solutions*

Several studies propose solutions at various frequencies. In this case [117], simulations of designs at 28 GHz and 140 GHz frequencies are analyzed. The first system, designed at 28 GHz, is similar to the current deployment of the 5G New Radio (NR) configuration [118]. The second system, at 140 GHz, uses the basis of an NR link and is the most likely for the future 6G generation [119]. In terms of design, for both cases, a patch antenna with oppositely truncated corners has been considered in order to achieve circular polarization. Given the arbitrary position of the UAV at any given time, circular polarization is ideal for this type of communications.

Other interesting antennas in UAV deployment are microstrip antennas, as they are low profile, lightweight and easy to manufacture and deploy, but limited in bandwidth [120]. Therefore, one of the main challenges in this type of antenna is to improve the bandwidth by reducing the size of the antenna [121]-[123]. In the article [124], a Ka/V dual-band microstrip antenna with a geometrical star shape, fed by a coaxial and printed on PCB has been proposed.

4.3 Advances in miniaturized antennas suitable for UAVs

Due to the increasing use of UAVs, there is a need for low profile, low weight and flexible antennas than can be integrated in a UAVs structure. However, electrically small antennas are known to suffer from low efficiencies and bandwidths. Several approaches have emerged to counteract these challenges. One of them focuses on antennas consisting of meandered wires to reduce their size, as well as loading the radiator with parasitic loops [125]-[127]. Another uses low-weight dielectric materials to realize high-gain antennas [128]. By far the most popular way to realize miniaturized antennas that are suitable for UAVs though, is the use of metamaterials, that is, artificial structures that exhibit unusual electromagnetic properties [129]. A collection of related publications is given in the table below.

Reference	**Operating frequencies (GHz)**	**Element type**	**Miniaturization technique**
[125]	0.433-0.434	Electric dipole	Folded
[126]	2.07–2.6, 2.86–3.57, 4.59–5.39	Patch	Loading vias
[127]	0.69-0.96	Bowtie	Parasitic structures
[128]	6.7-18.2	Dielectric horn	Dielectric lens

[130]	2.3-2.8 6-6.5	Patch	Metamaterial

4.4 Intelligent beamforming techniques for dynamic coverage and capacity optimization

4.4.1 Introduction

Intelligent beamforming techniques have become crucial in optimizing dynamic coverage and capacity in drone-based communication. Drones offer unparalleled mobility and flexibility, making them ideal for applications where coverage needs to adapt to changing target areas. This section explores two critical aspects of intelligent beamforming techniques in drone-based antennas: beamforming for dynamic coverage and capacity optimization.

4.4.2 Literature Survey

Intelligent beamforming techniques are crucial in optimizing coverage and capacity in drone-based communication systems. In [131], the use of 3-D beamforming in millimeter-wave (mmWave) unmanned aerial vehicle (UAV) communications is investigated. They propose a flexible coverage approach using a phased uniform planar array and subarray technique. [38] addresses the challenge of uplink coverage enhancement in sub-6 GHz 5G NR systems. They propose an adaptive digital beamforming technique based on cross-polarized array antennas. This approach mitigates the limitations of mobile station beamforming and improves the uplink channel quality, enhancing the downlink beamforming performance.

Authors in [132] explore dual polarization beamforming using a 5G New Radio (NR) MIMO radio system. They design dual polarized precoders to maximize coverage by utilizing all power amplifiers, resulting in a wide sector beam. The study highlights the potential of dual polarization beamforming to improve coverage and capacity in cellular systems. In [133], they focus on mmWave-based beamforming for capacity maximization in UAV-aided maritime communication systems. They propose an optimization problem formulation integrating multi-antennas beamforming with mmWave communication to enhance network performance. Simulation results show that the proposed mmWave beamforming approach helps improve backhaul capacity. In [134], antenna array beamforming strategies for efficient coverage and capacity in the high-altitude platform (HAP) systems are investigated. They propose an intelligent beamforming scheme based on dynamic adaptation using K-means clustering. The results indicate that the K-means clustering scheme outperforms random and regular pointing techniques, providing superior coverage and capacity while minimizing interference on terrestrial systems.

These techniques offer solutions for enhancing communication performance in UAV systems, sub-6 GHz 5G NR networks, maritime communication networks, and HAP systems. The studies highlight the effectiveness of beamforming in achieving flexible coverage, increasing capacity, and minimizing interference.

4.4.3 Intelligent Beamforming

Intelligent beamforming is instrumental in drone-based communication links. It enables precise control and shaping of antenna radiation patterns and beams, improving coverage and capacity through adaptive signal processing. In drone-based antennas, intelligent beamforming involves dynamic beam steering to point the main beam toward specific areas of interest. This flexibility allows efficient resource allocation and helps to adapt to changing coverage requirements or serving multiple users/regions. Beam shaping is another critical aspect of intelligent beamforming, where the radiation patterns are modified to achieve desired coverage objectives. Beamforming helps concentrate beams toward the target coverage area to maximize the gain and directivity while helping minimize interference and shape the radiation pattern to improve the signal quality and user experience.

Intelligent beamforming methods utilize adaptive mechanisms and learning algorithms to continuously adjust beamforming parameters based on channel conditions and environmental factors. This adaptability helps obtain optimal coverage and capacity in dynamic communication environments. Intelligent beamforming is crucial for optimizing coverage and capacity in drone-based communication systems. As research continues, intelligent beamforming will further enhance the capabilities and efficiency of drones in various applications, from disaster management to aerial connectivity.

4.4.4 Beamforming for Dynamic Coverage in Drone-Based Antennas

Dynamic coverage is essential for UAV communications as a drone's target coverage area can regularly change. The channel and the communication link can vary quickly as a drone changes its location. mmWave beamforming with phased arrays has emerged as a practical choice due to its compact size and power efficiency. One approach to achieve flexible coverage is through 3D beamforming with phased arrays. The footprint of the steered beams can cover target regions for which coordinate transformations can be used to characterize these regions. Subarray techniques can then be applied to design wide beams that cover selected areas. This approach helps achieve flexible beam coverage for different target areas, with most of the beamforming gain concentrated within the desired region.

Drones operate in dynamic environments and cover various areas while continuously changing positions. It is essential to provide adaptive coverage solutions to ensure uninterrupted wireless connectivity. By continuously adapting the coverage area, dynamic beamforming optimizes signal strength, reduces interference from surrounding objects, and improves the network performance.

4.4.5 Beamforming for Capacity Optimization in Drone-Based Antennas

Capacity optimization is a critical aspect of drone-based communication systems. The capacity of a communication channel depends on the average SNR and, consequently, the link quality. In 5G NR systems, digital beamforming with cross-polarized array antennas has shown promise in enhancing uplink coverage and capacity. Supporting multiple drones simultaneously and providing high-rate communication links are essential with the increasing number of drones in operation. Intelligent beamforming techniques are vital to optimize capacity by beam steering toward targeted drones. The antenna array maximizes the signal quality and throughput by focusing the energy, effectively enhancing the data rate. Spatial division multiple access (SDMA) and precoding techniques are explored as valuable techniques to help obtain successful schemes for helping multiple users and service areas or sectors. By allocating different beams to serve a particular coverage area, communication systems can benefit from antenna arrays' interference suppression and high directivity benefits.

4.4.6 Conclusion

All in all, intelligent beamforming techniques are vital in addressing the challenges of dynamic coverage and capacity optimization in drone-based communication systems. Through 3D beamforming, drones can achieve flexible coverage by adapting to changing target areas, ensuring efficient resource allocation. Moreover, digital beamforming with cross-polarized array antennas enhances capacity optimization by improving uplink coverage and channel estimation performance. These techniques contribute to advancing drone-based communication systems, enabling efficient and adequate coverage and capacity optimization. As intelligent beamforming continues to evolve, further research and innovation are expected to unlock new possibilities for deploying drone-based communication systems with improved performance, flexibility, and efficiency.

5 Performance Evaluation Metrics

5.1 Key performance indicators for non-terrestrial network antennas

Key performance indicators (KPIs) are instrumental in assessing the performance and efficacy of non-terrestrial network antennas. These antennas, meticulously engineered to deliver communication services within remote or demanding environments encompassing satellites, drones, and high-altitude platforms, necessitate the employment of precise KPIs for the evaluation of their operational functionality and operational efficiency. Several noteworthy KPIs for non-terrestrial network antennas comprise:

Signal Quality Metrics:

- Signal Strength: This metric quantifies the power level of the received signal, serving as an indicator of the antenna's capability to capture and sustain a robust signal.
- Signal-to-Noise Ratio (SNR): The SNR assesses the ratio between the power of the desired signal and the level of background noise, providing insights into the clarity and dependability of the signal.
- Error Rates: This metric evaluates the number of errors or bit errors present in the received signal, shedding light on the accuracy and integrity of the transmitted data.

Coverage and Capacity Metrics:

- Link Budget: The link budget computation encompasses the comprehensive assessment of total gains and losses within a communication link, accounting for essential factors such as antenna gains, path loss, and interference. This calculation serves to determine the extent of coverage and the range achievable by the link.
- Throughput: Throughput quantifies the data transfer rate between the transmitter and receiver, effectively indicating the antenna's capacity to handle data traffic with efficiency and proficiency.
- Spectral Efficiency: Spectral efficiency evaluation pertains to the measurement of how effectively the antenna exploits the available frequency spectrum, facilitating the attainment of higher data rates within the designated bandwidth.

Interference Management and Coexistence Metrics:

- Interference Rejection: This metric evaluates the antenna's efficacy in mitigating and rejecting external sources of interference, thereby ensuring the establishment of resilient and dependable communication links.

- Coexistence with Other Systems: This metric assesses the antenna's proficiency in operating harmoniously without causing or experiencing interference when coexisting alongside other communication systems or networks.

QoS Metrics:

- Latency: This metric quantifies the time delay experienced in transmitting data between the source and destination, exerting influence over the responsiveness and real-time performance of applications.

- Jitter: Jitter evaluates the variation in latency or delay, providing insights into the stability and consistency of data transmission.

- Reliability: Reliability assesses the antenna's capacity to consistently deliver a reliable and uninterrupted communication service, minimizing disruptions or service outages.

By monitoring and analyzing these key performance indicators, stakeholders can obtain valuable insights into the signal quality, coverage and capacity, interference management, and QoS aspects of non-terrestrial network antennas. These metrics facilitate informed decision-making, performance optimization, and the attainment of desired service levels in non-terrestrial communication scenarios. However, similar to any design, several factors contribute to the variation in the prioritization of key performance indicators (KPIs) for non-terrestrial network antennas. These factors encompass:

1. Use Cases and Network Requirements: Various applications and network requirements possess distinct demands and priorities. For instance, a surveillance application may prioritize low latency and dependable signal quality, whereas a data-intensive application may prioritize high throughput and spectral efficiency. The specific use case and the desired performance of the network determine the selection and prioritization of relevant KPIs.
2. Environment and Deployment Conditions: Non-terrestrial antennas function within a multitude of environments, ranging from space to airborne platforms and demanding terrestrial locations. Each environment introduces unique challenges, encompassing fluctuating weather conditions,

sources of interference, and limitations in power resources. To adequately address these specific environmental factors and deployment conditions, the KPIs must be customized accordingly.

3. Network Architecture and Design: The comprehensive network architecture and design exert influence over the prioritization of KPIs. Elements such as the quantity of interconnected antennas, network topology (e.g., point-to-point, mesh), and the inclusion of ground stations can significantly impact the performance prerequisites and, consequently, the selection and prioritization of pertinent KPIs.
4. User Requirements and Expectations: The requirements and expectations of end-users or customers exert a substantial influence on the prioritization of KPIs. Distinct user segments may exhibit diverse needs and preferences. For example, commercial users may prioritize cost-effectiveness, whereas government users may prioritize security and reliability.
5. Technological Advancements: The swift progression of technology brings forth novel capabilities and functionalities in the realm of non-terrestrial network antennas. These advancements often warrant the incorporation of new KPIs to appraise the performance of emerging technologies. For instance, the adoption of beamforming or advanced interference cancellation techniques may necessitate the inclusion of additional KPIs pertaining to beamforming gain or the antenna's proficiency in rejecting interference.
6. Regulatory and Standards Compliance: Regulatory requirements and industry standards often necessitate the establishment of specific KPIs for non-terrestrial network antennas. Conformity to these regulations and standards significantly shapes the selection and prioritization of KPIs, guaranteeing adherence to the designated performance benchmarks.

By taking these factors into account, stakeholders can ascertain the pertinent KPIs and establish their prioritization according to the precise context and objectives of the non-terrestrial network antennas. This approach enables a customized evaluation of performance and effective optimization to fulfill the specific requirements of the deployment. The subsequent subsections provide further elaboration on the KPIs.

5.2 Signal quality metrics: signal strength, signal-to-noise ratio, and error rates

In this section, we delve into the assessment of the “Signal Quality Matrix” ---a critical performance metric for Non-Terrestrial Networks (NTN) [6]. Specifically, we will discuss the characteristics of the received signal at the antenna port, an interface point that plays a key role in the network's overall performance.

In this regard, three main elements underpin the signal's quality, i.e., 1) the signal strength, 2) the signal-to-noise ratio (SNR), and 3) the error rate of the received signal. We provide a detailed examination of each of these parameters in the following subsections.

5.2.1 Signal Strength

Signal strength takes on additional significance in the context of analysing NTN system performance. The signal strength refers to the power level of the signal received at the antenna port, typically measured in volts per meter (V/m) or in decibel-milliwatts (dBm). This measure takes into account the power received after accommodating for losses incurred by the antenna and the cable. Given the challenges posed by NTNs, such as larger distances and atmospheric interference, maintaining high signal strength is crucial for the network's performance [135]. Higher signal strength equates to better signal quality. Conversely, low signal strength implies substantial losses, potentially disrupting communication if the signal strength dips below the system's average noise level. Therefore, within the scope of NTNs, signal strength is not the sole factor in assessing signal quality. It is typically evaluated alongside other key parameters to provide a more comprehensive view of the network's performance.

5.2.2 Signal to Noise ratio (S/N_0)

Signal to Noise ratio (SNR) is one of the most important parameters of a receiving system in any type of communication network. SNR is defined as the ratio between the signal power and the noise power present within the system [8]. Since, It’s a ratio between to power it is measured in terms of dBs.

$$SNR = \frac{P_{signal}}{P_{noise}}$$

Noise power is defined following.

$$P_{noise} = kTB$$

Where k is the Boltzmann’s constant having a value of 1.3806 x 10^{-23} $m^2kgs^{-2}K^{-1}$, T is the system temperature in Kelvin and B is the bandwidth in Hz.

SNR is a crucial performance metric in NTS system performance, reflecting a system's capability to distinguish the received signal from the inherent system noise. The wireless link budget of NTN plays a vital role here, influencing both the received signal's power and the noise level [137]. A high SNR translates to a superior quality received signal and it can be achieved by either amplifying the power of the primary signal or by reducing the noise levels. However, the wireless link budget constraints of NTNs mean that increasing the overall power isn't always a feasible solution, as it can lead to damage to the devices within the receiving chain and may also increase the overall energy consumption of the NTN. Noise levels in an NTN system largely depend on the operating frequency, with high-frequency systems often more susceptible to noise interference. Furthermore, the signal propagation characteristics and atmospheric conditions in NTNs can add to the noise level. Additionally, temperature plays a crucial role in noise power. Cooler systems typically present lower noise power compared to those operating at standard temperature ranges. Consequently, when considering an NTN's wireless link budget, balancing these factors to optimize SNR is critical for maintaining the robustness and reliability of the network.

5.2.3 Error Rate:

In any NTN-based digital communication system, the data transmitted over a channel may be distorted by factors such as path loss, reflections, and channel fading. At the receiving end, the signal is extracted from the noise through digital signal processing. However, this process cannot guarantee complete signal recovery. The system's ability to accurately transmit and receive signals is quantified using the ***Error Rate*** [136],[7]. This can be further categorized into Bit Error Rate (BER) and Packet Error Rate (PER).

BER: As implied by its name, the Bit Error Rate (BER) measures the proportion of erroneous bits received relative to the total number of bits transmitted. The formula is as follows:

$$BER = \frac{Number\ of\ bits\ in\ error}{Number\ of\ bits\ transmitted.}$$

Ideally, BER should be as low as possible to maintain high-quality communication. Elevated BER can degrade Quality of Service (QoS), leading to poor connections, packet loss, and signal distortion.

PER: The Packet Error Rate (PER) follows a similar definition given as:

$$PER = \frac{Number\ of\ packet\ in\ error}{Number\ of\ packet\ transmitted}$$

A packet is considered corrupted if at least one of its bit is received in error. Hence, PER is dependent upon the value of BER as well. However, PER becomes more significant when transmitting large volumes of data over extended periods. Both Error rates are defined for a specific value of SNR.

Relationship between BER and PER: The relationship between PER and BER can be defined by the following equation:

$$P_n = 1 - (1 - P_b)^n$$

Where P_n is the packet error rate, P_b is the bit error rate, and n is the total number of bits. In the context of NTN systems, careful management of error rates is crucial due to the challenging communication environment, which can introduce a higher likelihood of errors compared to terrestrial networks.

5.3 Coverage and Capacity Metrics:

In the context of a non-terrestrial network, such as satellite-based or aerial-based networks, the coverage and capacity matrices refer to the evaluation frameworks used to assess the network's coverage area and its capacity to support communication services. Important parameters to ensure a desired coverage and capacity is discussed next.

5.3.1 Link Budget

Link budget is the calculation performed to analyse power available in the system while considering all the losses and gain for a given system. The purpose of this calculation is to make sure that the signal after reaching its given destination has enough strength that system can achieve its desired performance. In satellite communication, link budget calculations are performed for the uplink and downlink communication separately. Even though received power is an important parameter of non-terrestrial communication system carrier-to-noise ratio (C/N_0) provides better insight into system's performance. Hence, link budget calculations will be performed to find the C/N_0.

Carrier to noise ratio can be found by consider the carrier received power w.r.t to the noise power present in the system. This can be presented in mathematical expression as

$$\frac{C}{N_0} = \frac{P_s}{kTB}$$

Here, P_s is the signal power, k is the Boltzmann constant, T is the system brightness temperature and B is the bandwidth of the system. Next, using this equation link budget calculations for uplink and downlink will be performed.

5.3.1.1 Uplink budget:

In uplink communication, ground link terminal is sending signal towards the satellite in space. In terms of system performance, the mathematical expression which can be used to calculate the received power P_r is given below [18].

$$\frac{C}{N_0} = EIRP + \frac{G}{T} - Losses - k - B$$

Here, C/N_0 is the Carrier to Noise density ratio of the satellite, G/T is the gain to temperature ratio of the receiving satellite antenna and, EIRP is the Effective Isotropic Radiated Power.

EIRP of a transmitting system can be described as

$$EIRP = GP_t$$

Similarly, Losses include Free Space Path Loss (FSPL), antenna misalignment loss, polarization mismatch, and atmospheric absorption loss. FSPL is a function of frequency, and it can be calculated using following equation

$$FSPL = (\frac{4\pi R}{\lambda})^2$$

5.3.1.2 Downlink Budget

A downlink communication is defined as when satellites send a signal to the ground terminal. For the downlink we can use the similar equation as uplink budget

$$\frac{C}{N_0} = EIRP + \frac{G}{T} - Losses - k - B$$

Here, G/T ratio of earth station will be used, also all the losses mentioned will be present at the earth station terminal.

5.3.2 Throughput

Throughput of the maximum data can be sent over a communication channel for a given channel bandwidth. Ideally, maximum throughput of a satellite channel can be found using Shannon channel capacity equation. For a given value of signal-to-noise ratio (SNR) and bandwidth B, we can define the channel capacity as

$$C = B * log_2(1 + SNR)$$

This is the maximum theoretical limit of channel capacity that can be achieved. Practically achieved throughput is always less than this value and spectral efficiency is the more practically realized data rate.

5.3.3 Spectral Efficiency

For two communication channels having same bandwidth, its performance can be measured by comparing its spectral efficiency. Spectral efficiency is the amount of data that can be transmitted for one user in the given system bandwidth.

$$\eta = \frac{R_b}{B_s}$$

Here, R_b is the data rate in bits per second (bps) and B_s is the bandwidth in Hz. Hence, the unit for spectral efficiency is bits/s/Hz. Spectral efficiency of a satellite system can also calculate using the SNR by following equation [2]

$$\eta = \frac{C/N}{E_b/N_0}$$

Here, C/N is the carrier to noise ratio and E_b/N_0 is the bit energy to noise power spectral density. Apart from CNR spectral efficiency is also a function of modulation scheme used in the communication channel.

5.4 Interference management and coexistence metrics

When a signal is being transmitted to the respective receiver, it can be affected by other interfering signals. For example, when a satellite is used to cover wide areas while applying a frequency reuse scheme, the side lobes of the radiated beams can create interference within the co-channel beams. In the following, we discuss some techniques to reduce this often undesired effect and we focus on satellite systems. We also review a number of metrics to address the coexistence of desired and interfering signals.

One technique that can be used to reduce co-channel interference due to frequency reuse is precoding, obtaining a high Signal-to-Interference-and-Noise Ratio (SINR). A precoding matrix is computed at the gateway, the beam signals are then preceded and transmitted via a feeder link using Frequency Division

Multiplexing (FDM). After this, the payload shifts the frequency of these signals and applies a reflector antenna fed by an array to transmit them over large areas using the multiple beams in the user link. The challenge in this scheme is to determine the precoding matrix, taken from a constrained maximization problem, where one seeks to maximize the sum-rate of the system (defined as the maximum possible data rate when considering multiple users). Such problem, however, is not convex and involves a large computational complexity. Alternative approaches, despite their lower complexity, still pose a number of challenges for implementation to cover large areas, thus being a relevant research topic. When using multiple gateways, other challenges might arise from a reduced degree of freedom in the precoding matrix design and channel state information acquisition.

Another alternative for interference reduction is applying signal processing techniques in the satellite, which has more degrees of freedom than on-ground processing and can be used to improve aspects such as latency, accessibility to information and support to emerging techniques (e.g., anti-jamming) [138]. Several paradigms can be used in this scenario, including regenerative processing, digital transparent processing and hybrid processing [139]-[141]. A case study in [138] shows the performance of several on-board detection strategies as a function of the Interference-to-Signal-and-Noise Ratio (ISNR).

In addition to the previously discussed techniques, it is possible to apply hybrid solutions, which share the spectrum of other communication systems, demonstrating the necessity of cognitive satellite systems. Also, due to low latency requirements, one can utilize techniques for integrated satellite-terrestrial backhauling for caching [138]. We discuss these strategies in more detail.

Satellite systems can either share the spectrum with ground or other satellite networks. In any case, spectrum awareness and exploitation are required steps. For spectrum awareness, radio environment mapping appears as a promising approach [142]-[143]. This can be done based on regulatory databases (which contain information such as antenna type and frequency band) or spectrum cartography (performing time and space estimation techniques to retrieve user information); in either case, these strategies produce a SINR matrix [138]. For spectrum exploitation, one performs resource allocation based on the available spectrum. As an example, one may seek to maximize the sum-rate under the carrier assignment orthogonality constraint [144]. In conjunction with this technique, non-orthogonal multiple access techniques might improve the overall performance.

In 5G systems, satellite and terrestrial architectures to increase backhauling capabilities appear as an alternative to provide coverage in areas with poor terrestrial infrastructure. They enable a reduced load of backhaul networks on Earth, deeper edge caching and full control of physical until application layers [138]. Furthermore, it is possible to tackle problems such as the allocation of resources across many modes of delivery (i.e., every node poses a different cost and with a different amount of bits to the covered users) and application coded caching prior to transmission, which can add a caching gain.

International regulations state that the interference inflicted from non-geostationary satellites should not degrade the performance of geostationary ones. In particular, the effective power flux density in the frequency bands allocated to geostationary systems also at any point covered by from their orbits should not exceed pre-established the limits pre-established by the International Telecommunication Union (ITU). This becomes a more difficult task, since these limits were defined more than 20 years ago and as more LEO satellite-based systems are increasingly being deployed. Given this scenario, some coexistence aspects need to be taken into consideration. Apart from the mentioned effective power flux density issue, the required infrastructure on Earth to operate a growing number of non-geostationary satellites can be significantly demanding, so they can negatively impact the services carried out to other users within the same frequency range [145].

5.5 QoS metrics

Quality of Service (QoS) in satellite communication refers to the level of performance and service attributes provided to users, ensuring that communication services meet certain predefined standards and expectations. QoS considerations are crucial in satellite communication systems to ensure satisfactory user experience and support various applications that require reliable and efficient data, voice, or video transmission.

Here are some key aspects related to QoS in satellite communication:

5.5.1 Latency

Latency is the amount of delay needed for a signal to travel from one point to another inside a network. Depending upon the type of communication channel (optical fibre, coaxial cables or a wireless channel) used this delay can vary from a few milliseconds to a hundred of millisecond. In any satellite communication link, this delay is the comprised of the time taken by the signal to reach the satellite, known as propagation delay, as well as the processing time performed at different locations of a network.

If we analyse the propagation delay specifically, the speed of the signal remains constant at speed of light but depending upon the height of the satellite used in the communication this delay can change drastically. In Low Earth Orbit (LEO) satellites, height of the satellite can be seen at the altitude of 780 km to up-to nearly 1400kms, causing a delay starting from 4.3ms to 7.8ms per hop. If the altitude of the satellite is increased further going to 8000kms, Medium Earth Orbit (MEO) satellite, provides a greater delay around 100msecs per hop. At the end, the satellite placed at the highest altitude of nearly 36000km, Geostationary satellite, expected delay increased to a nearly 500ms per hop.

Once type of the satellite has been selected for the communication link, this propagation delay will be fixed. On the other hand, processing delay is second contributor to the latency. Following reasons can be looked at to optimize the delay caused a communication network.

- Many network device has intelligent routing algorithm added to them to optimize the network traffic. For instance, many network layer 3 devices like router and switches can have decision making model through which traffic is filtered and routed to their designated port. If a network has a configurable device like switches or a router, processing time needed for its operability will increase the time delay.

- If the network has a serial communication port, network traffic will be queued at the terminal depending upon the derail port capacity. If the delay caused by the traffic is high, increasing the capacity of the serial port can decease the delay
- Many network devices have error corrections schemes implemented to decrease the bit error rate. Selection of the schemes is important to reduce the delay caused in the system
- TCP protocol to TCP fast start implementation

Depending upon the type of the application in which non-terrestrial communication is used, latency issue can be reduced by selecting a LEO satellite instead of MEO or GEO satellite. Further, this delay can be addresses by the optimizing the delay caused by the network processing.

5.5.2 Jitter:

In any communication link, a large amount of data is divided into smaller segments and sent in an order to a transmitting link. After travelling through the network, data is received in the same sequences as it was sent, and the output data is combined to generate the result. In this mechanism, it is assumed that the data travelling is experiencing an equal delay and hence it will receive in the same order it was sent in. However, in a real world the data can experience variable delay, causing the order to receiving packet to change. This variable delay is known as Jitter. Jitter can cause packet loss, delay as well as poor quality of the received signal. Jitter is important in time sensitive application. Jitter always occur in a network in which traffic is added in queue based on a priority assigned by the network administrator. Jitter can be introduced by the network terminal, as data is added in queue. In LEO satellite network, fast movement of a satellite can add jitter in the network. If a user handover needs to be performed between satellite, data travelling in the network can also experience latency.

5.5.3 Reliability:

Reliability in satellite communication refers to the ability of a satellite system to consistently and dependably provide communication services without interruptions or significant degradation in performance. It encompasses the network's ability to maintain a stable and reliable connection between the satellite and the ground stations, ensuring the successful transmission and reception of data, voice, or video signals.

Several factors contribute to the reliability of satellite communication:

- **Satellite System Redundancy**: Redundancy measures are implemented in satellite systems to ensure continuity of service even in the event of failures or malfunctions. This includes redundant satellites, ground stations, and critical subsystems, such as power systems, transponders, and control systems. Redundancy helps minimize the impact of single points of failure and improves overall system reliability.
- **Link Availability**: Satellite communication systems must maintain a high link availability, which refers to the percentage of time the satellite is operational and able to establish and maintain communication links. Factors that affect link availability include satellite orbit,

orbital positioning, antenna pointing accuracy, and atmospheric conditions. Effective monitoring and management of the link are crucial for maintaining reliability

- **Error Correction and Modulation Techniques**: Robust error correction coding and modulation techniques are employed in satellite communication to mitigate signal degradation and improve reliability. Techniques like forward error correction (FEC) and adaptive modulation schemes help compensate for signal impairments, interference, and atmospheric effects, thereby enhancing the reliability of data transmission.
- **Network Resilience**: Satellite communication networks often incorporate resilient network architectures and protocols to ensure reliability. This includes redundancy in network infrastructure, routing protocols that can adapt to network disruptions, and failover mechanisms to switch between redundant paths or satellites in case of failures [2].

5.6 Antenna Design Aspects for Synchronization Under Harsh Doppler

In a communication link, a Doppler shift happens whenever there is relative movement between transmitter and receiver. In satellite systems, this effect is more pronounced when the link happens involving a transmitter or receiver in LEO. On top of that, since frequencies in the mmWave range are expected to be used in future 6G technologies, this phenomenon might take place more severely. Therefore, the antenna design to reduce the Doppler effect is important to the deployment of communication systems within the previously described scenario. In the following, we analyze a number of aspects for the design of the antennas that may be used for proper deployment.

In environments heavily affected by Doppler shifts, one alternative to reduce such an effect is to apply adaptive beamforming techniques. With them, it is possible to modify the beam pattern of the transceivers towards the desired direction. By doing that, the signal power can be enhanced and the Doppler effects lowered. In this scenario, an emerging technology is the Intelligent Reconfigurable Surface (IRS). It consists of low-cost reflective elements with reconfigurable parameters that can be used to modify the respective beams accordingly, also providing a new paradigm to overcome challenges involving fading and interference in wireless channels [147]. An application example where Doppler shifts are a considerable challenge is using UAVs as base stations. The use of IRSs in a UAV-based system in the 200-400GHz range was investigated in [148]. In the studied case, the synergy between the IRS capabilities and the movement freedom of the UAV is explored by optimizing for the vehicle trajectory, phase shift and sub-band allocation. Simulations have shown that the minimum average rate (in Mbps) can be increased for different user equipments while following a shorter trajectory, consequently reducing the energy consumption.

By using Multiple-Input Multiple-Output (MIMO) technology one can explore spatial diversity to reduce Doppler shifts, also creating highly directive beams. Despite a large number of challenges associated with the use of the mmWave frequency range, the synergy between IRSs and a large number of small antennas has demonstrated promising results [149]-[151]. In addition, extremely large MIMO systems have the potential to be used in environments with harsh Doppler [147]. For example, they can be deployed in surfaces such as building walls and avenues [152]-[153].

To guarantee “anytime, anywhere” connectivity in future 6G systems, satellites shall play a major role to provide connectivity to mobile devices, ultra-high capacity links and improved link security. In this context, multi-antenna systems can be an important factor to guarantee such services. Nowadays, manufacturing techniques and processing capabilities are available to deploy, e.g., direct radiating arrays and support dynamic beamforming [154]. One promising scheme to provide system scalability and fault tolerance is forming large apertures using fractionated architectures [155]. To cover the Earth, this could be translated to a constellation constituted of about 100 small satellites in LEO [154]. Apart from that, with the aid of direct radiating arrays and massive MIMO strategies, it is possible to achieve very flexible beam steering, which can help reduce the effect of Doppler shifts. The operational requirements can be lowered by utilising hybrid beamforming schemes [156].

6 Emerging Trends and Future Directions

6.1 Integration of NTN antennas with 5G and beyond

Integrating Non-Terrestrial Network (NTN) antennas with 5G and future wireless technologies holds substantial potential for enhancing connectivity and enabling global coverage. NTN pertains to the incorporation of satellite-based communication systems as a complement to terrestrial networks, presenting diverse integration opportunities with these advanced technologies. The subsequent points outline crucial considerations for integrating NTN antennas with 5G and beyond:

- Extended Coverage: The deployment of NTN antennas in satellite constellations provides a means to extend the coverage of 5G networks to remote areas, rural regions, and geographically complex terrains. Through the ability to establish direct communication with user devices from space, NTN antennas offer a significantly wider coverage footprint in comparison to conventional terrestrial networks. This enables the provision of connectivity in previously underserved locations, ensuring that users in remote and challenging environments can benefit from the advantages of 5G technology.
- Seamless Handover: The integration of NTN antennas with 5G networks enables smooth handover mechanisms between terrestrial and satellite networks, guaranteeing uninterrupted connectivity for users during transitions across different coverage areas. When users move from a terrestrial cell to an area with limited or no terrestrial coverage, the connection can seamlessly transfer to NTN antennas situated in space, thus ensuring continuous provision of services. This seamless handover capability optimizes user experience by maintaining uninterrupted connectivity and mitigating service disruptions when transitioning between coverage zones with varying network availability.
- Network Resilience: The integration of NTN antennas significantly augments network resilience and reliability. In instances where terrestrial infrastructure is compromised or damaged due to natural disasters, NTN antennas serve as a resilient communication solution, ensuring uninterrupted connectivity. Acting as a backup option, they sustain the availability of communication services even during emergency scenarios. By leveraging satellite-based architecture, NTN antennas offer a robust and independent communication pathway that mitigates the vulnerability of terrestrial networks to physical disruptions, thus enhancing the overall resilience of the network infrastructure.
- High-Speed Connectivity: The primary objective of 5G and future wireless technologies is to achieve exceptional data rates and minimal latency. Through the integration of NTN antennas, these high-speed connections can be extended to remote and underserved areas, effectively addressing the

digital divide. This expansion of connectivity creates opportunities for a diverse range of applications, including remote healthcare, distance learning, and the deployment of Internet of Things (IoT) devices in previously inaccessible regions. By providing robust and high-capacity connectivity, NTN antennas contribute to the equitable distribution of digital resources, enabling transformative services and bridging the gap between digitally connected and underserved communities.

- Hybrid Network Architecture: The integration of a hybrid network architecture, incorporating both terrestrial 5G infrastructure and NTN antennas, presents an opportunity to optimize the utilization of available resources. Terrestrial networks demonstrate efficacy in high-density urban areas and regions with adequate coverage, while NTN antennas excel in providing connectivity to rural and remote areas. This synergistic combination enables efficient allocation of resources, ensuring optimized network performance. By leveraging the strengths of both terrestrial and satellite-based systems, the hybrid network architecture maximizes coverage, capacity, and user experience, thus facilitating a more robust and adaptable communication infrastructure.
- Future Satellite Systems: In addition to the advancements made in 5G technology, there are ongoing plans to develop advanced satellite systems, including Low Earth Orbit (LEO) mega-constellations, aimed at providing global coverage and high-speed connectivity. In this context, the seamless integration of NTN antennas with these forthcoming satellite systems holds great promise in further augmenting the robustness and scalability of communication networks. By integrating NTN antennas with future satellite systems, the overall network infrastructure can be strengthened, enabling enhanced global coverage, improved data rates, and expanded communication capabilities. This integration paves the way for a new era of communication technology, facilitating ubiquitous connectivity and catering to the increasing demands of a digitally connected world.

Successful integration of NTN antennas with 5G and future wireless technologies requires a high degree of collaboration among satellite operators, terrestrial network providers, and regulatory bodies to ensure seamless integration and interoperability. This collaborative effort is vital to harmonize technical standards, spectrum allocation, and regulatory frameworks, thereby enabling the smooth operation of the integrated network infrastructure. The transformative potential of this integration is significant, as it has the capability to revolutionize connectivity on a global scale. By providing ubiquitous coverage, the integration of NTN antennas with advanced wireless technologies can bridge the digital divide, ensuring equitable access to communication services and fostering socio-economic development worldwide. This collaborative approach serves as a catalyst for the evolution of a connected society, enabling enhanced communication capabilities and paving the way for a more inclusive and globally connected future.

6.2 Advancements in materials for lightweight and high-performance antennas

Recent advancements in high-performance antennas are made possible both by the creation and study of new materials as well as by improvements and breakthroughs in manufacturing technology. Concerning the former, a classification of the main categories of these new exotic materials with unusual properties and promising applications is found below.

- Metamaterials:
  The properties of metamaterials are derived from their nano-scale physical structure, not from their chemical composition. They are artificially designed micro and nano-structural units forming a lattice, allowing the designer to tune their properties as desired [157].

  The topic of metamaterials is vast and multidisciplinary, with countless possible interesting properties and applications. Reducing the scope to antenna engineering, key applications of metamaterial may be further subdivided into the following categories:

  - Double Negative / Left-Handed Materials:
    Metamaterials permit the synthesis of structures with simultaneously negative permittivity (ε) and permeability (μ), which does not occur in nature. These structures are referred to as Left-Handed Materials (LHM) or Double Negative (DNG) materials. Figure 6.1 classifies the different combinations of ε and μ signs. EM waves may only propagate in the first and third quadrant; the other two regions only allow evanescent (non-propagating) waves.

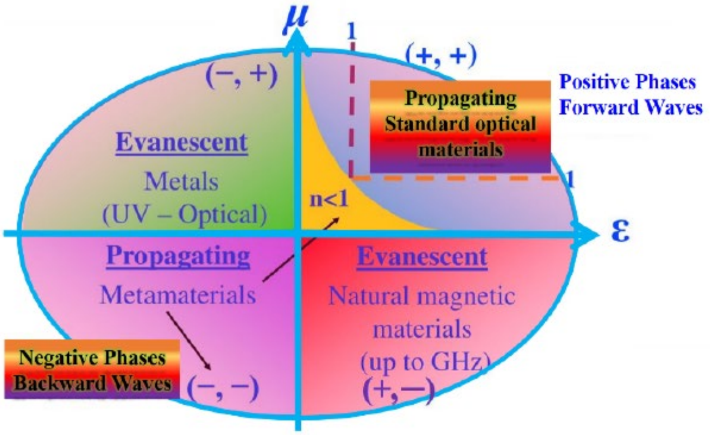


Figure 6.1. Classification of metamaterials based on their permittivity (ε) and permeability (μ) [1].

Applications for LHMs include mutual coupling reduction and miniaturization [158] as well as increases in bandwidth, gain, and efficiency [159]. Metamaterials may also be tunable in real time by applying external stimuli, such as DC voltage [160].

- Anisotropic structures:

  A structure or material is anisotropic if it presents different properties in different directions. This is in contrast to isotropic materials, whose properties remain unchanged in all axes. Metamaterials may achieve this by having their micro or nano-structures oriented in a certain way or presenting some kind of symmetry in only certain directions.

  In antenna engineering, perhaps the most common type of anisotropy is polarization response. This means reflection/transmission of the metamaterial changes depending on the type or sense of the polarization used. For example, in [161], a metasurface reflectarray antenna is fed by two orthogonal linear polarizations, which can then generate different circular or elliptical polarizations by virtue of the contrasting responses of the surface to the two incoming feed sources. In [162], an anisotropic ring is positioned around an omnidirectional antenna in order to circularly polarize its initial linear polarization output, therefore eliminating the need for a second radiating element. This can be seen in Figure 6.2 below.

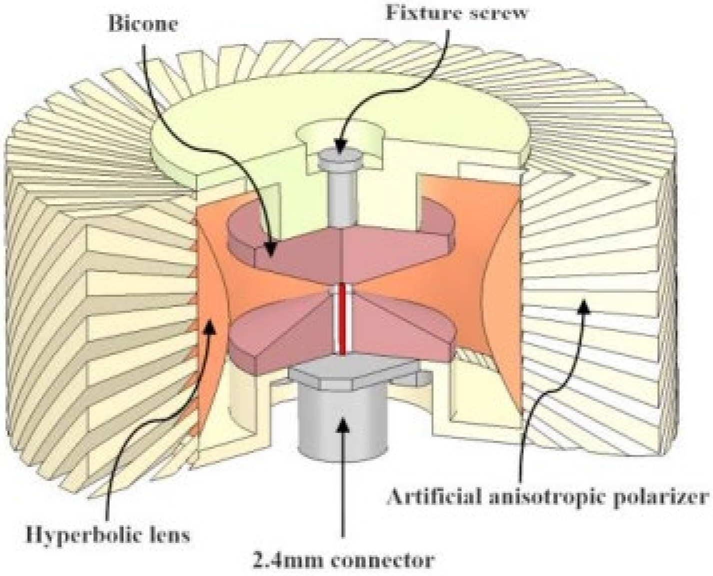


Figure 6.2. Geometry of the omnidirectional circularly-polarized antenna [6].

Anisotropic metamaterials may also be applied to improve existing antenna types, as is done in [163], where a Fabry-Pérot cavity antenna is constructed with two metasurfaces acting as ends of the cavity.

Another key application of anisotropic materials is reconfigurability and beamsteering [164]. Examples include tunable resonant-cavity antennas with beamsteering via rotating interlocked metasurfaces [165] and bandwidth enhancement and beamsteering of a Fabry-Pérot cavity antenna [166]. In [167], an anisotropic Dielectric Resonator Antenna (DRA) is combined with a water layer on top. The antenna can switch between two states, one using the DRA directly, and the other acting as a "liquid" patch antenna by making use of the water layer with the DRA as substrate.

- Electromagnetic Band Gap structures:

  Electromagnetic Band Gap (EBG) structures either prevent or enable the propagation of EM waves at certain frequencies, irrespectively of the incident angle or polarization state of the wave in particular [168], a 6-sector antenna with EBGs as unit cells is combined with an antenna array. PIN diodes activate and deactive the EBGs as required in order to steer the resulting beam of the antenna.

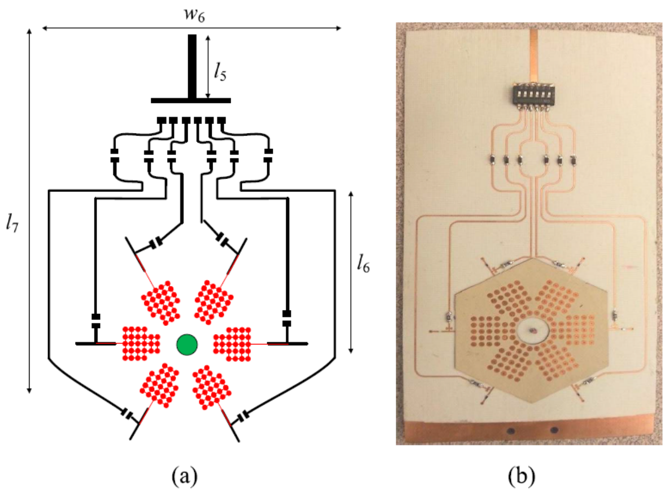


Figure 5.3 (a) Schematic view of the antenna. (b) Fabricated prototype. [12]

- Magneto-Dielectric substrates:

Usually, substrates display solely dielectric properties, with their relative permittivity depending on the PCB thickness and other criteria. Traditionally, to decrease antenna and RF circuit dimensions, high-permittivity dielectric substrates are used. However, problems encountered with this technique include lowered gain, radiation pattern degradation, impedance matching issues, among others. If magnetic inclusions are embedded into the substrate, creating a magneto-dielectric material, these negative effects can be mitigated [169].

Nevertheless, using exclusively magneto-dieletric substrates negatively impacts radiation efficiency. To solve this, magneto-dielectric materials may also be combined with regular dielectric materials in multi-layered substrates to improve performance in miniaturization while keeping efficiency at reasonable levels [170].

- Microwave-absorbing materials

  As their name indicates, Microwave-Absorbing Materials (MAMs) dampen EM waves. Several types of materials may be used to that effect, from plasma-based technologies [171] all the way to coating paint loaded with ferrite particles [172]. In fact, it is possible to employ metamaterials to perform the role of MAMs, as is done in [173] . MAM radiation absorption may be either wideband or frequency selective.

  MAMs can be incorporated into existing antenna technologies to improve their performance, decrease mutual coupling and reduce their size. For example, in [174], a Vivaldi antenna is improved by covering its outer edges, where distortion patters usually form, with an ultra-thin membrane of MAM. As another example, in [175], the use of MAMs on a dipole antenna allows the designers to increase the bandwidth by 6.3%.

Regarding manufacturing techniques, the main innovation this last decade is undoubtedly Additive Manufacturing (AM). This is not limited[1] to the domain of antenna engineering: AM is nowadays a ubiquitous sight in any subject of research related to manufacturing and fabrication. Unlike traditional Subtractive Manufacturing (SM), where material is removed from a starting block (by means of milling, machining, etc.) until the desired geometry is obtained, AM sequentially adds material to build the shape from scratch.

AM can be classified into 7 types [176]: Vat Photopolymerization, Powder Bed Fusion, Binder Jetting, Material Jetting, Directed Energy Deposition, Sheet Lamination and Material Extrusion. Among these, perhaps the most extensively used in antenna technologies are Material Extrusion (also known as 3D printing), Vat Photopolymerisation (where radiation selectively cures resin to create complex shapes) and Powder Bed Fusion (focused lasers or electron beams fuse a powder bed of the material to form the 3D part).

The key reasons for using AM over SM in antenna engineering may be summarized as follows: (1) Creation of complex shapes not suitable for SM and/or (2) Rapid prototyping of pieces that would be too long to manufacture using SM, all while (3) Ensuring performance of AM antennas is as good as or better than their SM counterparts.

Reason (1) is perhaps the main driver behind AM in antenna engineering. As showcased in [177], there are certain types of “pathological” antenna shapes that are outright unfeasible to manufacture in SM. The

---

[1]

3D Hilbert fractal antenna studied by the authors is a clear example. The antenna, constructed using three AM techniques, is shown in 6.4.

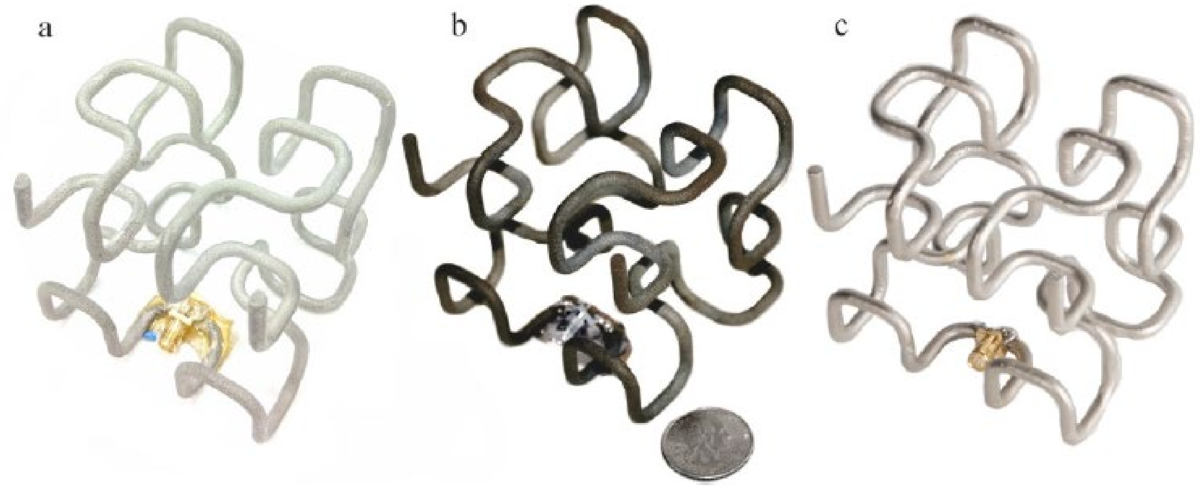


Figure 6.4. Hilbert 3D fractal antenna manufacture comparison. a) Laser Powder Bed Fusion, b) Binder Jetting, c) Vat Photopolymerization with plating [21].

For reason (2), it is shown in [178] that, given that AM techniques are faster than SM for certain prototyping and manufacturing phases (but not all of them), the ideal option is to combine both into a harmonized process. This yields RF components much faster than traditional options while still being reliable. In particular, they combine water-jet laser cutting with 3D printing to produce hollow substrate integrated waveguides not only faster, but with an increased performance as well.

Concerning reason (3), [179] compares the AM techniques of Direct Metal Laser Sintering (DMLS) and Stereolithography (SLA) to the well-established SM method of milling. Three equal antennas are built using the three techniques and their characteristics are contrasted, demonstrating that performance is similar between the three. Additionally, inherent criteria corresponding to each method are also compared, with AM techniques having the edge in weigh reduction, but lagging behind in surface finish and accuracy. Other works comparing antennas constructed using AM and SM techniques include:

- A comparison between a machining, selective laser melting, and binder jetting for a Ka-band antenna array [180]. The authors show identical radiation patterns for all three arrays, even though the arrays built using AM present a loss of 0.5 – 1.5 dB in realized gain.
- Efficiency measurements of electrically small antennas using AM [181]. It is revealed that the rough metallization adds some discrepancies between simulated and measured S parameters, although these tend to be minor.
- A dual-band antenna manufactured using AM and SM techniques, whose performance is then compared [182]. Excellent agreement between the characteristics of both antennas is found.

6.3 AI and ML for antenna optimization and self-healing

In recent years, the application of Artificial Intelligence (AI) and Machine Learning (ML) techniques has revolutionized the field of antenna technology, enabling major advancements in optimization capabilities. AI and ML algorithms have empowered engineers to automate the antenna design process, exploring a vast design space to achieve optimal performance metrics such as radiation pattern, gain, and impedance matching. Traditionally, antenna design has relied on manual expertise and trial-and-error methods. However, with the use of AI and ML, it is possible to automate the design process and explore a much larger design space to find optimal solutions.

The work in presents a focused and comprehensive literature survey on the use of ML in antenna design and optimization. In fact, introduced a novel inverse design approach in which the optimal structural parameters for a desired response are obtained by querying a learned database of similar optimal structures rather than applying direct optimization (as is the case with the conventional procedures). The authors demonstrated that, the Generative Adversarial Networks (GANs) can be utilized as a learned, data-driven antenna database and queried for fast generation of new designs like the ones that it was trained with. Furthermore, the work in [59] propose an automated antenna design method that combines imitation learning (IL) and reinforcement learning (RL). Through training the RL agent in diverse antenna states, a robust antenna tuning policy that outperforms pure RL policies is obtained. This study demonstrates the effectiveness of incorporating human guidance as a supplement to RL for improved antenna tuning. In addition, ML techniques such as Gaussian Processes or Neural Networks can be used to create surrogate models of the antenna performance. These models can approximate the relationship between the antenna design parameters and its performance characteristics, allowing for faster optimization and exploration of the design space.

Moreover, AI and ML algorithms facilitate self-healing antennas which is the ability of an antenna system to automatically detect and recover from faults or performance degradation without manual intervention by enabling real-time monitoring, fault detection, fault localization, and adaptive optimization. These self-healing antennas can autonomously detect anomalies, identify faults, and take corrective actions, minimizing downtime and ensuring continuous and reliable antenna performance. The work in [60] present a focused and comprehensive literature survey on the use of ML in antenna design and optimization. discusses the challenges in data-driven ML algorithms for self-healing and provide some potential solution directions for addressing these issues. Additionally, it provides a case study of cost-sensitive fault detection with imbalanced data to illustrate the feasibility and effectiveness of the suggested solutions.

In fact, AI plays an important role in anomaly detection by monitoring antenna behaviour, identifying deviations from expected performance using real-time or historical data. Its techniques also assist in fault diagnosis, employing classification or clustering algorithms to analyse performance data and locate faults. Moreover, these algorithms facilitate adaptive beamforming, continuously adjusting the antenna's radiation pattern in response to changing environmental conditions, optimizing signal reception, and minimizing interference.

A recent example of AI applied to antenna design is relevant to meta lenses. Using ML, revolutionary designs and performances far exceeding conventional designs were developed [183]. ML is interesting for Reconfigurable intelligent Surfaces or simply RIS, as it provides a unique development within it. ML can provide design optimization as seen similarly with meta lens, but this is only on antenna level. But RIS also provides a revolutionary view on propagation making it controllable parameter in a network. An AI can be used to utilize RIS to its fullest potential, transforming the radio environment to a Smart Radio Environment known as SRE. To utilize SRE optimally for a network, AI usage is necessary as SRE are highly complex and difficult to interpret without an AI. SRE are essential for a future with high dynamic environments with rapid changing demands within the network. Ai can be used to design such SRE to interact with the environment intelligently having characteristics like perceiving, problem solving, learning and more [184]. With forementioned characteristics, the SRE can for example solve issues on itself caused by natural or human made disasters thus restoring it network dynamically therefore self-healing itself on macroscopic level as well as on microscopic hardware level such singular element failures within a RIS system/environment. Conclusion is that AI and ML are essential for the next generations networks, whether it is NTN or TN.

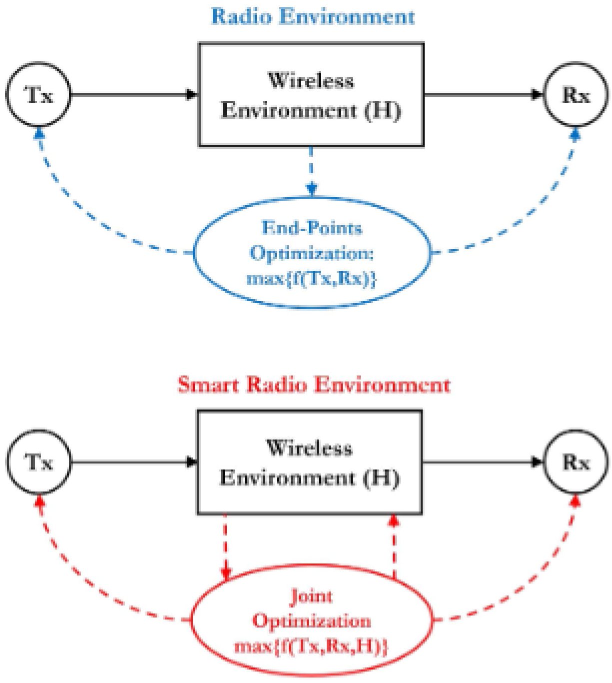


Figure 6.5, Smart Radio Environment made possible by RIS[4]

Overall, AI and ML techniques offer promising approaches for optimizing antenna designs and enabling self-healing capabilities. These technologies can enhance the performance, reliability, and adaptability of antenna systems in various applications.

6.4 Hybrid networks and seamless handover between terrestrial and non-terrestrial systems

Hybrid networks refer to the integration of different types of communication systems, combining terrestrial (ground-based) and non-terrestrial (satellite-based) networks. These networks aim to provide seamless connectivity and handover capabilities between these systems, ensuring uninterrupted communication for users.Terrestrial systems typically include cellular networks, Wi-Fi, and other land-based communication infrastructure. They offer localized coverage, high data rates, and low latency. On the other hand, non-terrestrial systems encompass satellite networks, such as geostationary satellites (GEO), medium Earth orbit satellites (MEO), and low Earth orbit satellites (LEO). These satellite systems provide global coverage and are particularly useful in areas with limited or no terrestrial infrastructure [185] – [189].

Seamless handover is the process of transferring an ongoing communication session from one network to another without disruption. In the context of hybrid networks, seamless handover involves the smooth transition of a user's communication session between terrestrial and non-terrestrial systems as they move across coverage areas. One possible solution is to use diversified wireless networks that can exploit the inter-connectivity between satellites, aerial base stations (BSs), and terrestrial BSs over inter-connected space, ground, and aerial network. According to the work in [190], there are a lot the EU-funded initiatives under Horizon 2020 that aims to establish connectivity in “problem terrain” away from dense urban and suburban populations like, the shared-access terrestrial–satellite backhaul network enabled by smart antennas (SANSA) [191], the satellite and terrestrial network for 5G (SAT5G) [192], the 5G agile and flexible integration of satellite and cellular (5G ALL-STAR) [193],[194], and the Hybrid networks for global internet access [195].

In this integrated architecture, there are two types of handovers in the integrated satellite-terrestrial network: the first is called horizontal (intranetwork) handover while the second is known as the vertical (internetwork) handover [196]. The horizontal handover occurs when the connection is transferred between terres- trial cells, between satellite spot-beams, or between satellites. In contrast, the vertical handover occurs when the connec- tion is transferred between the terrestrial network and the satellite network. For the horizontal handover, since the handover occurs solely in the terrestrial network or the satellite network, it can be performed by the conventional handover techniques in each network [197],[198]. On the other hand, there are more challenges for the vertical handover in the inte- grated satellite-terrestrial network, in which the connection is transferred between two different networks. In [199], a new handover mechanism was proposed for the integrated satellite-terrestrial network to enable handovers between satellite and terrestrial components. The handover decision and preparation processes are sepa- rated to reduce the probability of failure for long handover preparation cases.

To achieve seamless handover between terrestrial and non-terrestrial systems in hybrid networks, several challenges need to be addressed. First, network interoperability is crucial as terrestrial and non-terrestrial networks operate on different protocols and architectures. Ensuring compatibility and interoperability between these systems is essential for seamless handover, requiring the development of standardized interfaces and protocols that can facilitate seamless communication and transfer of data between the networks. Second, mobility management plays a critical role in the handover process. As users move between coverage areas, efficient mobility management techniques must be in place to track and manage their location and connectivity status. This involves continuously monitoring the user's movement, estimating their position, and coordinating the handover process to ensure uninterrupted connectivity during the transition. Third, signal quality and latency considerations are vital for achieving a smooth handover experience. The handover decision should consider the signal quality and latency of both the source and target networks. Seamless handover requires evaluating the available network resources, such as signal strength and bandwidth, to determine the optimal moment for handover initiation. This ensures a seamless transition without significant disruptions or delays in communication. Fourth, authentication and security are paramount in handover scenarios. Handovers should be secure to protect user data and prevent unauthorized access. Robust authentication mechanisms need to be in place to verify the user's identity during the handover process, ensuring that only authorized users gain access to the networks. Encryption and authentication protocols play a crucial role in maintaining data security during handovers.

Overall, the integration of terrestrial and non-terrestrial systems in hybrid networks, along with seamless handover capabilities, aims to extend connectivity reach, enhance user experience, and provide reliable communication services across diverse geographic locations [200]-[203].

6.5 Standardization efforts and regulatory frameworks for NTN antenna technology

Standardization and regulation have a crucial role in the development of future Non-Terrestrial Networks (NTNs). The benefits from the standardization process are [204]: for example, standardization allows for multi-vendor interoperability, and in that sense, it fosters competition. This in turn will provide cost reduction for NTN satellite technology and accelerated development of the space segment of the wireless networks. Another aspect of the standardization is to ensure maximum spectrum efficiency and compatibility with already deployed terrestrial wireless networks and help maintain safety and performance standards.

In this subsection, the focus is on the standardization efforts [205] and regulatory framework from the Third Generation Partnership Project (3GPP)[2] . The goal is not to present the overall work that 3GPP has done on NTN networks, but to select the standards or regulatory framework that is the most important for the development of new NTN antenna technology. That is, the focus will be on the standards that influence the architecture and design of the NTNs physical layer. An overview of the 3GPP work on evolving 5G wireless technology to support NTN satellite networks is found in reference [206]. Considerations for future 6G networks can be found in reference [207]. The next four paragraphs summarize the important points from the 3GPP standards Rel-15, Rel-16, Rel-17, and uncompleted Rel-18.

---

[2] https://www.3gpp.org/

The first study on New Radio to support NTNs was conducted in 3GPP Release 15. The main conclusions are found in Technical Report (TR) 38.811 [208]. This technical report identifies the relevant scenarios for NTN deployment studies and integration in terms of: frequency bands (S-band at $2\ \mathrm{GHz}$ vs. K and K_a-band at $20-30\ \mathrm{GHz}$), typical footprint size and minimum elevation angles, antenna models and beam configurations (Earth-fixed, steered towards a fixed area on the ground, vs. moving beams), and NTN terminals (handheld vs. VSAT). The report also specifies the propagation channel models based on TR 38.901 [209] with NTN-specific modifications.

In Rel-16, the objectives of the Study Item (SI) on "Solutions for NR to support Non-Terrestrial Network" were to consolidate the potential impact on the physical layer as initially identified in TR 38.811 and the identification of related solutions if needed. Solutions for NR to support NTNs were identified in TR 38.821 [210]. The TR is focused on FR1[3] for handheld and IoT satellite access, and it identifies modifications required for the physical and higher layers. It also studies the impact of delay on random access, scheduling, as well as mobility management for moving LEO platforms.

The standards continued to build upon the 3GPP Rel-17 with the architectural aspects for using satellite access in 5G considered in TR 23.737 [211]. The TR specifies enhancement for RF and physical layer, protocols, radio resource management, and frequency bands. It identifies suitable architectures, it addresses TN-NTN roaming and timing-related issues, enhanced conditional handover, and location-based triggering.

Rel-18 is still in development. The focus in the new release is on improving the NR NTN to provide better support for NTN in smartphones, while also introducing K_a band (above 10 GHz) for applications involving very small aperture terminals. The improvements in smartphone support coverage will involve extending the current repetition schemes, implementing mechanisms to address diversity and polarization loss caused using linear polarizations at terminals and circular polarizations at satellites, as well as reducing protocol overhead to efficiently support low-rate codecs.

Since the completion of 3GPP Release 15 – the first phase of 5G specifications – the cellular industry is expanding the capability of the network to deliver on the full promise of true connectivity. Release 18 will deliver 5G-Advanced, as the mid-point of 5G standardization. Standardization efforts are ongoing and it is expected to be completed in 6G [212] when we will have a complete integration of NTNs and TNs in one global system.

The standardization process is long and on-going, so it is expected that the standards will develop over time. An important take way note from this standardization process is the way they will influence the development of NTN antennas. The most important standards and requirements to look out for when designing NTN antennas can be grouped in five points:

1. Type of access (direct or indirect).
2. Beam spot size.

---

[3] Frequency range 1 is sub $6\ \mathrm{GHz}$

3. Frequency range
4. Movable or fixed beam
5. Other (regional) regulatory requirements

Besides 3GPP, it must be mentioned the effort on standardization by the European Telecommunications Standards Institute (ETSI). The Satellite Earth Stations and Systems technical committee (TC SES) is the technical body within ETSI that is responsible for creating standards for satellite terminals (earth stations) and systems. This work notably includes the development and revision of Harmonized Standards[4] covering all aspects of satellite earth station fixed terminals or terminals on the move, whether in an aircraft, on board a ship or in a vehicle.

6.6 Antennas with Integrated Photonics RF Front-end

For many years, photonic devices and subsystems have been seen as technologies that enable the generation, transmission, detection, processing, and control of microwave signals in radio frequency (RF) systems [213]. The growth and success of the field of microwave photonics have been propelled by the inherent advantages it offers. These advantages include wide input bandwidths, precise timing, low-loss and electromagnetic interference-free signal transportation, lightweight and flexible cabling, and signal multiplexing that enables reduced cabling. A significant drawback that has stood out is the inefficient conversion between the microwave and optical domains, along with the introduction of additional noise and distortion. These factors have hindered the realization of the complete potential of photonics. However, recent advancements in integrated photonics have showcased promising prospects for the near-future implementation of photonic subsystems.

Integrated photonics front-ends in satellite communication are an emerging trend that has been stimulated by the recent advancement of integrated photonics. In literature, the field that deals with generating, processing, and transporting microwave signals in the optical domain using integrated photonic systems can be found under the name of Integrated Microwave Photonics (IMWP) [214]. In this subsection, recent advancement and trends in antennas with integrated photonics RF front-ends [215] will be discussed. The focus will be on the following topics: Optical beamforming networks (OBFNs), photonics signals transport (with and without frequency conversion), and optical switching. Other research topics that are interesting for antenna systems in satellite payloads, and integrated antenna/electro-optic modulators, will be mentioned.

Future satellite payloads in the next generation of non-terrestrial networks are expected to have beamforming and beam hopping capabilities to dynamically allocate data capacity to the regions in the earth where there is demand. So, there is a need for scalable, power-efficient, small formfactor, reliable and light weight BFNs. Due to its intrinsic properties, as mentioned in the opening paragraph, integrated photonics is the perfect candidate for building BFNs.

In a multibeam satellite payload, a beamforming network controls the direction of the radiated beams. Beamforming networks can be divided into two categories [216]: phase-shifter-based systems and true-

---

[4] The report can be found in [ETSI - Activity Report SES]

time-delay-based systems. The former employs phase shifters to adjust the phase of radiated signals so that the signals from different radiated elements can interfere with each other constructively at aimed directions, while the latter controls the time delay of each radiated signal so that the signals arrive at the target destination simultaneously.

The main limitation of phase-shifter-based OBFNs is the beam-squint effect: once a wideband signal is applied to the OBFN, the beam direction changes according to the RF signal frequency. Wideband beamforming is crucial for managing variations in beam bandwidth because future software-defined payloads need to possess the ability to allocate bandwidth. In the case of a K_a-band software defined satellite, for example, a $3\ \mathrm{GHz}$ bandwidth can be allocated to one single-spot beam.

In 1991, optical fiber-based OBFNs utilizing true-time-delay (TTD) modules were initially proposed and demonstrated using bulk components – for e.g., optical fibers, as the means to implement wideband beamforming [217]. Recently, an OBFN-PIC was designed to facilitate the steering of a microwave signal with carrier frequency up to $40\ \mathrm{GHz}$ over a continuous set of beam angles [218]. reference [219], a 1×4 optical beamforming chip was introduced and tested. It incorporated four integrated switchable delay line units, specifically designed to control a phased antenna array operating in the K_a-band. By measuring the delay times, the optical beamforming network's directional patterns were simulated, resulting in a beam angle coverage of $90°$. Additionally, a magnitude response experiment was conducted to assess the performance of the optical beamforming chip, revealing an impressive operational bandwidth of $29\ \mathrm{GHz}$. The size of the fabricated device is $4.2\ \mathrm{mm} \times\ 5\ \mathrm{mm}$.

Microwave mixers are an integral part of the RF front-end in any satellite payload because the uplink and downlink frequencies differ. Compared with its electronic counterpart, and optical microwave mixer advantages in terms of large bandwidth and high isolation [220]. Moreover, parallel frequency conversion can be implemented using WDM technology [221], which is an attractive prospect for multichannel signal processing in satellite payloads.

The most common method for optical microwave mixing implementation involves utilizing a Mach-Zehnder modulator (MZM). In this method, the optical local oscillator (LO) signal and the driven radio frequency (RF) signal are multiplied by leveraging the Pockels electro-optic effect [222] within the MZM [223]. If multiple optical LO signals are sent to the MZM, all LOs are combined with the RF signal to generate multiple IF signals at the same time. For example, taking advantage of the optical LOs generated by the OFC[5], a $6.1\ \mathrm{GHz}$ C-band signal can be converted to $4.1\ \mathrm{GHz}$ (C-band), $3.9\ \mathrm{GHz}$ (C-band), and $11.9\ \mathrm{GHz}$ (X-band), etc., signals simultaneously [224] Although the microwave photonics mixing of RF signals is a promising application, there is still necessity of improving the MZM-based optical mixing performance include enhancing conversion efficiency, linearity, and functionality in order to be used in telecom systems.

RF switches utilized in satellite payloads to realize signal routing, function switching, and system reconfiguration [225]. Traditionally, RF switches are applied in the electrical domain, in which the working

---

[5] Optical Frequency Combs

bandwidth, switching speed, and isolation between channels are always limited. Optical techniques are beneficial in terms of wide working bandwidth and immunity to EMI, so switching of RF signals in the optical domain can potentially overcome electronic limitations.

Integrated photonics is a very promising area of research for satellite communication purposes [215]. During the past 20 years optical beamforming concepts have been demonstrated for microwave signals. OBFNs have already been implemented with phased array antennas and their performance is very good. Mixing, filtering, and switching are also very important functions in a RF front-end, and they can be implemented with integrated photonics. Integrated photonics represents a technological change in the satellite payloads which has the potential to be highly beneficial for future satellite telecom payloads

7 References

[1] S. Euler, X. Fu, et al. “Using 3GPP technology for satellite communication”, 2023, URL: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/3gpp-satellite-communication

[2] Wang, Cheng-Xiang, et al. "On the road to 6G: Visions, requirements, key technologies and testbeds." IEEE Communications Surveys & Tutorials (2023).

[3] Vaezi, Mojtaba, et al. "Cellular, wide-area, and non-terrestrial IoT: A survey on 5G advances and the road toward 6G." IEEE Communications Surveys & Tutorials 24.2 (2022): 1117-1174.

[4] O. Kodheli et al., "Satellite Communications in the New Space Era: A Survey and Future Challenges", IEEE communications surveys & tutorials (2021).

[5] 3GPP Technical Report TR 38.821, “Solutions for NR to support non-terrestrial networks (NTN)”, Release-16.2, URL:https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525

[6] M. M. Azari, S. Solanki, S. Chatzinotas, O. Kodheli, H. Sallouha, A. Colpaert, J. F. M. Montoya, S. Pollin, A. Haqiqatnejad, A. Mostaani, E. Lagunas and B. Ottersten, "Evolution of Non-Terrestrial Networks From 5G to 6G: A Survey," *IEEE Communications Surveys & Tutorials,* vol. 24, no. 4, pp. 2633-2672, 2022.

[7] M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," IEEE Network, vol. 35, no. 2, pp. 244 - 251, 2020.

[8] J. Zhang, X. Zhang, P. Wang, L. Liu and Y. Wang, "Double-edge intelligent integrated satellite terrestrial networks," IEEE Network, vol. 17, no. 9, 2020.

[9] A. Sattarzadeh, Y. Liu, A. Mohamed, R. Song, P. Xiao, Z. Song, H. Zhang, R. Tafazolli and . C. Niu, "Satellite-Based Non-Terrestrial Networks in 5G: Insights and Challenges," IEEE, vol. 10, pp. 11274 - 11283, 2022.

[10] Y. Islam Demir, M. S. J. Solaija and H. Arslan, "On the Performance of Handover Mechanisms for Non-Terrestrial Networks," in 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), Helsinki, 2022.

[11] G. Araniti, F. Rinaldi, S. Pizzi and A. Iera, "Toward 6G Non-Terrestrial Networks," IEEE Network, vol. 36, no. 1, 2022.

[12] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey," IEEE Open Journal of the Communications Society, vol. 2, pp. 334 - 366, 2021.

[13] F. Hsieh, F. Jardel, E. Visotsky, F. Vook, A. Ghosh and B. Picha, "UAV-based Multi-cell HAPS Communication: System Design and Performance Evaluation," in GLOBECOM 2020 - 2020 IEEE Global Communications Conference, Taipei, 2020.

[14] H. Kitanozono, J. Suzuki, Y. Kishiyama, Y. Hokazono, T. Sotoyama, M. Ouchi, R. Miura and H. Tsuji, "Development of High Altitude Platform Station Backhaul System Using 38GHz Band Frequency," in 2021 IEEE VTS 17th Asia Pacific Wireless Communications Symposium (APWCS), Osaka, 2021.

[15] D. Tuzi, T. Delamotte and A. Knopp, "Satellite Swarm-Based Antenna Arrays for 6G Direct-to-Cell Connectivity," IEEE Access, vol. 11, pp. 36907-36928, 2023.

[16] N. Cassiau, G. Noh, S. Jaeckel, L. Raschkowski, J.-M. Houssin, L. Combelles, M. Thary, J. Kim, J.-B. Dore and M. Laugeois, "Satellite and Terrestrial Multi-Connectivity for 5G: Making Spectrum Sharing Possible," in 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Seoul, 2020.

[17] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy and G. Araniti, "Non-Terrestrial Networks in 5G & Beyond: A Survey," IEEE Access, vol. 8, pp. 165178 - 165200, 2020.

[18] William A. Imbriale; Steven (Shichang) Gao; Luigi Boccia, "Emerging Antenna Technologies for Space Applications," in Space Antenna Handbook , Wiley, 2012, doi: 10.1002/9781119945147.ch11.

[19] J. N. Pelton, S. Madry, and S. Camacho-Lara, Handbook of Satellite Applications. New York, NY, USA: Springer, 2013.

[20] S. Liu et al., "LEO Satellite Constellations for 5G and Beyond: How Will They Reshape Vertical Domains?," in IEEE Communications Magazine, vol. 59, no. 7, pp. 30-36, July 2021

[21] Butash, T., Garland, P. and Evans, B. (2021), Non-geostationary satellite orbit communications satellite constellations history. Int J Satell Commun Network, 39: 1-5.

[22] K. Tekbiyik, G. K. Kurt, A. R. Ektı and H. Yanikomeroglu, "Reconfigurable Intelligent Surfaces Empowered THz Communication in LEO Satellite Networks," IEEE Access, vol. 10, pp. 121957 - 121969, 2022.

[23] Z.-J. Guo, Z.-C. Hao, H.-Y. Yin, D.-M. Sun and G. Q. Luo, "Planar Shared-Aperture Array Antenna With a High Isolation for Millimeter-Wave Low Earth Orbit Satellite Communication System," IEEE Transactions on Antennas and Propagation, vol. 69, no. 11, pp. 7582-7592, 2021.

[24] J. C. Lafond, E. Vourch, F. Delepaux, P. Lepeltier, P. Bosshard, F. Dubos, C. Feat, C. Labourdette, G. Navarre and J. M. Bassaler, "Thales Alenia Space multiple beam antennas for telecommunication satellites," in The 8th European Conference on Antennas and Propagation (EuCAP 2014), The Hague, 2014.

[25] Y. Rahmat-Samii and A. C. Densmore, "Technology Trends and Challenges of Antennas for Satellite Communication Systems," IEEE Transactions on Antennas and Propagation, vol. 63, no. 4, pp. 1191 - 1204, 2015.

[26] S. K. Rao, "Advanced Antenna Technologies for Satellite Communications Payloads," IEEE Transactions on Antennas and Propagation , vol. 63, no. 4, pp. 1205 - 1217, 2015.

[27] S. Anguix, A. Araghi, M. Khalily and R. Tafazolli, "Reflectarray Antenna Design for LEO Satellite Communications in Ka-band," in 2021 15th European Conference on Antennas and Propagation (EuCAP), Dusseldorf, 2021.

[28] E. Amyotte, Y. Demers, V. Dupessey, M. Forest, L. Hildebrand, A. Liang, M. Riel and S. Sierra-Garcia, "A summary of recent developments in satellite antennas at MDA," in Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), Rome, 2011.

[29] P. Lepeltier, J. Maurel, C. Labourdette, F. Croq, G. Navarre and J. David, "Thales Alenia Space France Antennas: Recent Achievements and Future Trends for Telecommunications," in The Second European Conference on Antennas and Propagation, EuCAP 2007, Edinburgh, 2007.

[30] G. Toso, C. Mangenot and P. Angeletti, "Recent advances on space multibeam antennas based on a single aperture," in 2013 7th European Conference on Antennas and Propagation (EuCAP), Gothenburg, 2013.

[31] S. J. Stirland and A. D. Craig, "Phased Arrays for Satellite Communications: Recent Developments at Astrium Ltd," in The Second European Conference on Antennas and Propagation, EuCAP 2007, Edinburgh, 2007.

[32] P. Angeletti, C. Mangenot and G. Toso, "Recent advances on array antennas for multibeam space applications," in 2013 IEEE Antennas and Propagation Society International Symposium (APSURSI), Orlando, 2013.

[33] J. F. Zhang and Y. J. Cheng, "K-/Ka-Band Planar Shared-Aperture Beam-Scanning Array Antenna for Simultaneous Transmitting and Receiving Low Earth Orbit Satellite Communication Terminal," IEEE Transactions on Antennas and Propagation , 2023.

[34] F. Filice, N. Nachabe, C. Luxey and F. Gianesello, "3D-Printed Double-Ridged Waveguide Array Antenna targeting High-Efficiency Ku-band SatCom on The Move Applications," in 2019 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), Atlanta, 2019.

[35] T. Chaloun, L. Boccia, E. Arnieri, M. Fischer, V. Valenta, N. J. G. Fonseca and C. Waldschmidt, "Electronically Steerable Antennas for Future Heterogeneous Communication Networks: Review and Perspectives," IEEE Journal of Microwaves , vol. 2, no. 4, pp. 545 - 581, 2022.

[36] J. Park, B. Kim, J. Choi, A. A. Omar and W. Hong, "Heterogeneous Phased Array Architecture Consisting of AoD and AiP to Enhance Spherical Beamforming Coverage for 5G/6G Celullar Handsets," in 15th European Conference on Antennas and Propagation (EuCAP), Dusseldorf, Germany, 2021.

[37] Q. Zhang, S. Gao, L. Wen and X. -X. Yang, "Ultra-Thin Low-Cost Electronically-Beam-Scanning Reflectarray for Ka-Band Satellite Communications on the Move and 6G," in International Workshop on Antenna Technology (iWAT), Dublin, Ireland, 2022.

[38] Y. -J. Song, S. -J. Lim, S. -K. Lee and J. -S. Jang, "Adaptive Digital Beamforming for Uplink Coverage Enhancement in 5G NR System," in 27th Telecommunications Forum (TELFOR), Belgrade, Serbia, 2019.

[39] G. Aruna and B. S., "Capacity and SNR Analysis of A Millimeter Wave Cellular Network with Phased Antenna Array," in International Conference on Computer Communications and Informatics (ICCCI), Coimbatore, India, 2018.

[40] M. Matalatala, M. Deruyck, E. Tanghe, L. Martens and J. W., "Simulations of Beamforming Performance and Energy Efficiency for 5G mm-Wave Cellular Networks," in IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, 2018.

[41] S. Suyama, T. Okuyama, N. Nonaka and T. Asai, "Recent Studies on Massive MIMO Technologies for 5G Evolution and 6G," in IEEE Radio and Wireless Symposium (RWS), Las Vegas, NV, USA, 2022.

[42] G. Yang, Y. Zhang and S. Zhang, "Wideband and Wide-Angle Scanning Phased Array Antenna for Mobile Communication System," IEEE Open Journal of Antennas and Propagation, vol. 2, pp. 203-212, 2021.

[43] Sudhakar Rao, Minh Tang, Chih-Chien Hsu and Jim Wang, "Advanced antenna technologies for satellite communication payloads," *2006 First European Conference on Antennas and Propagation*, Nice, 2006, pp. 1-6.

[44] E. Amyotte *et al*., "A summary of recent developments in satellite antennas at MDA," *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, Rome, Italy, 2011, pp. 3203-3207.

[45] A. G. Roederer, "Antennas for Space: Some Recent European Developments and Trends," *2005 18th International Conference on Applied Electromagnetics and Communications*, Dubrovnik, Croatia, 2005, pp. 1-8

[46] L. Marcellini, R. Lo Forti and G. Bellaveglia, "Future developments trend for Ku and Ka antenna for satcom on the move," *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, Rome, Italy, 2011, pp. 2346-2350.

[47] J. C. Lafond *et al*., "Thales Alenia Space France antennas: recent achievements for telecommunications," *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, Rome, Italy, 2011, pp. 3193-3197.

[48] M. Lumia, G. Addamo, O. A. Peverini, F. Calignano, G. Virone and D. Manfredi, “Additive Manufacturing of RF Waveguide Components,” in Microwave Technologies, 2022.

[49] F. Calignano, D. Manfredi, E. P. Ambrosio, S. Biamino, M. Lombardi, E. Atzeni, A. Salmi, P. Minetola, L. Iuliano and P. Fino, “Overview on Additive Manufacturing Technologies,” Proceedings of the IEEE, vol. 105, no. 4, pp. 593 - 612, 2017.

[50] Z. Miller, B. Stidham, T. Fairbanks and C. Maldonado, “The Use of Stereolithography (SLA) Additive Manufacturing in Space-Based Instrumentation,” in 2023 IEEE Aerospace Conference, Big Sky, MT, USA, 2023.

[51] O. A. Peverini, G. Addamo, M. Lumia, G. Virone, F. Calignano, M. Lorusso and D. Manfredi, “Additive manufacturing of Ku/K-band waveguide filters: a comparative analysis among selective-laser melting and stereo-lithography,” IET Microw. Antennas Propag., vol. 11, no. 14, pp. 1936 - 1942, 2017.

[52] O. A. Peverini, M. Lumia, F. Calignano, G. Addamo, M. Lorusso, E. P. Ambrosio, D. Manfredi and G. Virone, “Selective Laser Melting Manufacturing of Microwave Waveguide Devices,” IEEE, vol. 105, no. 4, pp. 620-631, 2017.

[53] O. Neikov, N. A. Yefimov and S. Naboychenko, Handbook of Non-Ferrous Metal Powders, Elsevier, 2008.

[54] A. B. Spierings, N. Herres and G. Levy, “Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts,” Rapid Prototyping Journal, vol. 17, no. 3, pp. 195 - 202, 2011.

[55] M. Qian, “Metal Powder for Additive Manufacturing,” JOM: the journal of the Minerals, Metals & Materials Society, vol. 67, no. 3, 2015.

[56] S. Sirci, E. Menargues and M. Billod, “Space-qualified Additive Manufacturing and its Application to Active Antenna Harmonic Filters,” in 2021 IEEE MTT-S International Microwave Filter Workshop (IMFW), Perugia, Italy, 2021.

[57] G. Addamo, O. A. Peverini, D. Manfredi, F. Calignano, F. Paonessa, G. Virone, R. Tascone and G. Dassano, “Additive Manufacturing of Ka-Band Dual-Polarization Waveguide Components,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 8, pp. 3589 - 3596, 2018.

[58] F. Calignano, “Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting,” Materials and Design, vol. 64, 2014.

[59] M. Oldoni, S. C. Mejllones, S. C. Mejillones, S. Moscato and A. Giannini, "Ka-band Coaxial Horn Filtenna for Enhanced Electromagnetic Compatibility on Spacecraft," 2021 IEEE MTT-S International Microwave Filter Workshop (IMFW), Perugia, Italy, 2021, pp. 269-271, doi: 10.1109/IMFW49589.2021.9642276.

[60] R. Jennings, "The Challenge to Develop the Perfect Flat Panel Satellite Communications Terminal: The Perfect SATCOM Terminal," in *IEEE Microwave Magazine*, vol. 24, no. 5, pp. 22-29, May 2023, doi: 10.1109/MMM.2023.3242538.

[61] G. Amendola et al., "Low-Earth Orbit User Segment in the Ku and Ka-Band: An Overview of Antennas and RF Front-End Technologies," in IEEE Microwave Magazine, vol. 24, no. 2, pp. 32-48, Feb. 2023, doi: 10.1109/MMM.2022.3217961.

[62] P. P. Shome, T. Khan, S. K. Koul and Y. M. M. Antar, "Filtenna Designs for Radio-Frequency Front-End Systems: A structural-oriented review," in IEEE Antennas and Propagation Magazine, vol. 63, no. 5, pp. 72-84, Oct. 2021, doi: 10.1109/MAP.2020.2988518.

[63] C. X. Mao, Y. Zhang, X. Y. Zhang, P. Xiao, Y. Wang and S. Gao, "Filtering Antennas: Design Methods and Recent Developments," in IEEE Microwave Magazine, vol. 22, no. 11, pp. 52-63, Nov. 2021, doi: 10.1109/MMM.2021.3102199.

[64] S. S. Olokede and M. F. Ain, “A multifunctional antenna with a small form factor: Designing a novel series-fed compact triangular microstrip ring resonator antenna array,” IEEE Antennas Propag. Mag., vol. 60, no. 1, pp. 62–71, Feb. 2018. doi: 10.1109/MAP.2017.2774145.

[65] S. R. Mishra and S. K. Lalitha, “Implementation of defected ground structure for microstrip filtenna design,” Int. J. RF Microw. Comput. Aided Eng., vol. 30, no. 1, p. e21998, Oct. 2019. doi: 10.1002/mmce.21998.

[66] H. Li, X. Liang, X. Chen, X. Zhang and W. Wang, "Design of a Filtering Antenna with High Stopband Suppression for Ku-band Satellite Communications," 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA, 2022, pp. 1008-1009, doi: 10.1109/AP-S/USNC-URSI47032.2022.9886253.

[67] E. B. Lima, J. R. Costa and C. A. Fernandes, "Wideband and High-Selectivity Dual-Band Filter for Ka-Band Satellite Antennas," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1627-1630, 2017, doi: 10.1109/LAWP.2017.2657543.

[68] W. Yuan, X. Liang, L. Zhang, J. Geng, W. Zhu and R. Jin, "Rectangular Grating Waveguide Slot Array Antenna for SATCOM Applications," in IEEE Transactions on Antennas and Propagation, vol. 67, no. 6, pp. 3869-3880, June 2019, doi: 10.1109/TAP.2019.2905784.

[69] M. K. Moghaddam and R. Fleury, "A Subwavelength Microwave Bandpass Filter Based on a Chiral Waveguide," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135288.

[70] M. Al-Joumayly and N. Behdad, "A New Technique for Design of Low-Profile, Second-Order, Bandpass Frequency Selective Surfaces," in IEEE Transactions on Antennas and Propagation, vol. 57, no. 2, pp. 452-459, Feb. 2009, doi: 10.1109/TAP.2008.2011382.

[71] Z. Zheng, X. Fang, W. Wang, G. Huang, H. Zhang and X. Liang, "A Compact Waveguide Slot Filtering Antenna Based on Mushroom-Type Surface," in IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 10, pp. 1823-1827, Oct. 2020, doi: 10.1109/LAWP.2020.3020539.

[72] C. Fang, X. Liang, Y. Liu, Y. Gao, R. Jin and L. Zhang, "A K-band Dual-polarized Stepped Horn Filtenna," 2021 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Nanjing, China, 2021, pp. 1-3, doi: 10.1109/ICMMT52847.2021.9618596.

[73] P. -P. Zhang, M. Jiang, Y. Hu, P. Chu, X. -C. Zhu and G. -Q. Luo, "Design of Circularly Polarized Filtering Transmitarray Antenna With Linearly Polarized Feed," 2022 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Guangzhou, China, 2022, pp. 1-3, doi: 10.1109/IMWS-AMP54652.2022.10106797.

[74] Y. -D. Wang, X. -L. Liang, W. Wang, Y. -H. Tan and P. -K. Liu, "Ku-band Waveguide Slot Filtering Antenna Based on Metallic-Nail Metamaterial," 2020 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Shanghai, China, 2020, pp. 1-3, doi: 10.1109/ICMMT49418.2020.9386530.

[75] R. S. Hao, J. F. Zhang, S. C. Jin, D. G. Liu, T. J. Li and Y. J. Cheng, "K-/Ka-Band Shared-Aperture Phased Array With Wide Bandwidth and Wide Beam Coverage for LEO Satellite Communication," in IEEE Transactions on Antennas and Propagation, vol. 71, no. 1, pp. 672-680, Jan. 2023, doi: 10.1109/TAP.2022.3222091.

[76] J. Liu and L. Sun, "Design of Filtering Antenna for 5G FR2 Applications Using Characteristic Mode Analysis," in IEEE Antennas and Wireless Propagation Letters, doi: 10.1109/LAWP.2023.3247198.

[77] J. Guo, Y. Chen, D. Yang, B. Ma, S. Liu and J. Pan, "Design of a Circuit-Free Filtering Metasurface Antenna Using Characteristic Mode Analysis," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 12, pp. 12322-12327, Dec. 2022, doi: 10.1109/TAP.2022.3209717.

[78] J. -C. S. Chieh *et al*., "Development of Flat Panel Active Phased Array Antennas Using 5G Silicon RFICs at Ku- and Ka-Bands," in *IEEE Access*, vol. 8, pp. 192669-192681, 2020, doi: 10.1109/ACCESS.2020.3032841.

[79] C. Eric, "An Open Standard for Ka-band Interoperable Satellite Antennas," *MILCOM 2019 - 2019 IEEE Military Communications Conference (MILCOM)*, Norfolk, VA, USA, 2019, pp. 76-81, doi: 10.1109/MILCOM47813.2019.9020854.

[80] A. I. Sandhu, E. Arnieri, G. Amendola, L. Boccia, E. Meniconi and V. Ziegler, "Radiating Elements for Shared Aperture Tx/Rx Phased Arrays at K/Ka Band," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 6, pp. 2270-2282, June 2016, doi: 10.1109/TAP.2016.2552550.

[81] X. Chang, H. B. Wang, T. J. Li, S. C. Jin, D. G. Liu and Y. J. Cheng, "Shared-Aperture Phased Array Antenna With Codesigned Near-Field Coupled Circular Polarizer Loaded for K/Ka-Band Wide-Angle Satellite Communication," in *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 9, pp. 7478-7490, Sept. 2022, doi: 10.1109/TAP.2022.3196619.

[82] H. Kähkönen, J. Ala-Laurinaho and V. Viikari, "A Modular Dual-Polarized Ka-Band Vivaldi Antenna Array," in *IEEE Access*, vol. 10, pp. 36362-36372, 2022, doi: 10.1109/ACCESS.2022.3164201.

[83] S. M. Moghaddam, J. Yang and A. U. Zaman, "Fully-Planar Ultrawideband Tightly-Coupled Array (FPU-TCA) With Integrated Feed for Wide-Scanning Millimeter-Wave Applications," in *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 9, pp. 6591-6601, Sept. 2020, doi: 10.1109/TAP.2020.3001448.

[84] D. G. a. *M. Mohorcic, "Broadband Communications via High Altitude Platforms.," 2011.*

[85] O. A. a. A. Y. a. H. Y. a. N. D. D. a. G. S. a. P. Zhu, "HAPS for 6G Networks: Potential Use Cases, Open Challenges, and Possible Solutions," 2023.

[86] L. J. C. H. Z. L. a. D. H. P. Ji, "Energy-efficient beamforming for beamspace HAP-NOMA systems," vol. 25, no. 5, p. 1678–1681, 2021.

[87] N. K. M. K. K. H. Y. O. a. A. N. Y. Shibata, "System design of gigabit HAPS mobile communications," vol. 8, p. 157 995–158 007, 2020.

[88] M. S. J. L. D. Z. a. Z. H. Z. Jia, "Joint HAP access and LEO satellite backhaul in 6G: Matching game-based approaches," vol. 39, no. 4, p. 1147–1159, 2021.

[89] D. R. a. M. Meo, "Can High Altitude Platform Stations Make 6G Sustainable?," vol. 60, no. 9, pp. 75-80, 2022.

[90] F. H. A. G. a. T. S. R. Y. Xing, "High Altitude Platform Stations (HAPS): Architecture and System Performance," pp. 1-6, 2021.

[91] M. H. Capstick and D. Grace, ``High Altitude Platform mm-Wave Aperture Antenna Steering Solutions" Wireless Personal Communications, vol. 32, no. 3–4, pp. 215–236, Feb. 2005, doi: https://doi.org/10.1007/s11277-005-0743-2.

[92] J. A. Thornton, D. Grace, M. Capstick, and T. C. Tozer, "Optimizing an array of antennas for cellular coverage from a high altitude platform," IEEE Transactions on Wireless Communications, vol. 2, no. 3, pp. 484–492, May 2003, doi: https://doi.org/10.1109/twc.2003.811052.

[93] G.M. Djuknic, J. Freidenfelds, and Y. Okunev, "Establishing Wireless Communications Services Via HighAltitude Aeronautical Platforms: A Concept Whose Time Has Come?", IEEE Communications Magazine, Vol. 35, No. 9, pp. 128–35, September 1997.

[94] C. A. Balanis, Antenna theory analysis and design. New York, N.Y. Wiley, 1997.

[95] M. Letizia, J. -F. Zürcher, B. Fuchs, J. R. Mosig and A. Skrivervik, "Circularly polarized multi-beam lens antenna system for High Altitude Platforms (HAPS)," Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), Rome, Italy, 2011, pp. 1051-1055.

[96] A. Araghi, H. R. Hassani, F. Maleknia, and A. M. Montazeri, "A novel printed array contoured beam antenna on HAPs," in 6th International Symposium on Telecommunications (IST), Nov. 2012, pp. 98–101. doi: 10.1109/ISTEL.2012.6482963.

[97] K. Hoshino, S. Sudo, and Y. Ohta, "A Study on Antenna Beamforming Method Considering Movement of Solar Plane in HAPS System," in 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Sep. 2019, pp. 1–5. doi: 10.1109/VTCFall.2019.8891546.

[98] A. Alexander et. al., "Loon Library: Lessons from Building Loon's Stratospheric Communications Service", August 2021. URL: https://x.company/projects/loon/the-loon-collection/ . Latest access: 26 June 2023.

[99] M. Stoneback and K. Madsen, "A Planar All-Silicon 256-Element Ka-band Phased Array for High-Altitude Platforms (HAPs) Application," in 2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA: IEEE, 2018, pp. 783–786. doi: 10.1109/MWSYM.2018.8439632.

[100] K. Popoola, D. Grace, and T. Clarke, “Capacity and Coverage Analysis of High Altitude Platform (HAP) Antenna Arrays for Rural Vehicular Broadband Services,” in 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium: IEEE, 2020, pp. 1–5. doi: 10.1109/VTC2020-Spring48590.2020.9129557.

[101] S. Sudo, K. Hoshino, and Y. Ohta, “Basic Evaluation of Service Link Antenna for Footprint Fixation in HAPS System,” in 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada: IEEE, 2020, pp. 1–5. doi: 10.1109/VTC2020-Fall49728.2020.9348661.

[102] Y. Albagory, “An Adaptive Bidirectional Multibeam High-Altitude Platforms Aeronautical Telecommunication Network Using Dual Concentric Conical Arrays,” IEEE Access, vol. 9, pp. 43324–43338, 2021, doi: 10.1109/ACCESS.2021.3066091.

[103] Q. Xi, C. He, L. Jiang, J. Tian and Y. Shen, "Capacity Analysis of Massive MIMO on High Altitude Platforms," 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 2016, pp. 1-6, doi: 10.1109/GLOCOM.2016.7841647.

[104] K. Tashiro, K. Hoshino, and A. Nagate, “Cylindrical Massive MIMO System for HAPS: Capacity Enhancement and Coverage Extension,” in 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), Helsinki, Finland: IEEE, 2021, pp. 1–6. doi: 10.1109/VTC2021-Spring51267.2021.9449056.

[105] G. Otsuru, H. Tsuji, R. Miura, J. Suzuki, and Y. Kishiyama, “Efficient Antenna Tracking Algorithm for HAPS Ground Station in Millimeter-Wave,” in 2022 25th International Symposium on Wireless Personal Multimedia Communications (WPMC), Herning, Denmark: IEEE, Oct. 2022, pp. 261–266. doi: 10.1109/WPMC55625.2022.10014806.

[106] M. Handley, “Using ground relays for low-latency wide-area routing in mega constellations,” in Proc. ACM Workshop Hot Topics Netw.(HotNets), 2019, pp. 125–132

[107] G. Karabulut Kurt et al., ``A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future," in IEEE Communications Surveys & Tutorials, vol. 23, no. 2, pp. 729-779, Secondquarter 2021, doi: 10.1109/COMST.2021.3066905.

[108] Si-Mohammed, S., Bouaziz, M., Hellaoui, H., Bekkouche, O., Ksentini, A., Taleb, T., Tomaszewski, L., Lutz, T., Srinivasan, G., Jarvet, T., & Montowtt, P. (2021). Supporting unmanned aerial vehicle services in 5g networks: New high-level architecture integrating 5g with u-space. *IEEE Vehicular Technology Magazine*, *16*(1), 57–65. https://doi.org/10.1109/MVT.2020.3036374

[109] Azari, M. M., Solanki, S., Chatzinotas, S., Kodheli, O., Sallouha, H., Colpaert, A., Mendoza Montoya, J. F., Pollin, S., Haqiqatnejad, A., Mostaani, A., Lagunas, E., & Ottersten, B. (2022). Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey. *IEEE Communications Surveys and Tutorials*, *24*(4), 2633–2672. https://doi.org/10.1109/COMST.2022.3199901

[110] D. V. Navarro-Mendez, H. C. Moy-Li, L. F. Carrera-Suarez, M. Ferrando-Bataller and M. Baquero-Escudero, “Antenna arrays for unmanned aerial vehicle,” in 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal, 2015.

[111] C. Zhang, W. Zhang, W. Wang, L. Yang and W. Zhang, “Research Challenges and Opportunities of UAV Millimeter-Wave Communications,” IEEE Wireless Communications, vol. 26, no. 1, pp. 58 - 62, 2019.

[112] J. Zhao, F. Gao, Q. Wu, S. Jin, Y. Wu and W. Jia, “Beam Tracking for UAV Mounted SatCom on-the-Move With Massive Antenna Array,” IEEE Journal on Selected Areas in Communications, vol. 36, no. 2, pp. 363 - 375, 2018.

[113] J. Chen, J. Wang, K.-F. Tong and A. Al-Armaghany, “A GPS/Wi-Fi dual-band arc-shaped slot patch antenna for UAV application,” in 2013 Loughborough Antennas & Propagation Conference (LAPC), Loughborough, UK, 2013.

[114] M. S. Sharawi, D. N. Aloi and O. A. Rawashdeh, “Design and Implementation of Embedded Printed Antenna Arrays in Small UAV Wing Structures,” IEEE Transactions on Antennas and Propagation, vol. 58, no. 8, pp. 2531 - 2538, 2010.

[115] H. Wang, J. Wang, J. Chen, Y. Gong and G. Ding, “Network-connected UAV communications: Potentials and challenges,” China Communications, vol. 15, no. 12, pp. 111 - 121, 2018.

[116] Z. Xiao, L. Zhu and X.-G. Xia, “UAV communications with millimeter-wave beamforming: Potentials, scenarios, and challenges,” China Communications, vol. 17, no. 9, pp. 147 - 166, 2020.

[117] W. Xia, V. Semkin, M. Mezzavilla, G. Loianno and S. Rangan, “Multi-Array Designs for mmWave and Sub-THz Communication to UAVs,” in 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Atlanta, GA, USA, 2020.

[118] 3GPP, “TS 38.300, NR and NG-RAN Overall Description; Stage 2,” 2017.

[119] Y. Xing and T. S. Rappaport, “Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz,” in 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, United Arab Emirates, 2018.

[120] I. Bahl, M. Bozzi and R. Garg, Microstrip Lines and Slotlines, Artech, 2013.

[121] M. Abbaspour and H. Hassani, “WideBand star-shaped microstrip patch antenna,” Progress In Electromagnetics Research Letters, vol. 1, pp. 61 - 68, 2008.

[122] J.-S. Kuo and K.-L. Wong, “A compact microstrip antenna with meandering slots in the ground plane,” Microw. Opt. Technol. Lett., vol. 29, no. 95 - 97, 2001.

[123] A. Eldek, A. Elsherbeni and C. Smith, “Characteristics of Bow-Tie Slot Antenna with Tapered Tuning Stubs for Wideband Operation,” Progress In Electromagnetics Research, vol. 49, no. 53 - 69, 2004.

[124] S. Saad Siddiq, K. G.S, T. Tanjavur and N. Agnihotri, “Microstrip dual band millimeter-wave antenna array for UAV applications,” in 2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), Krakow, Poland, 2016.

[125] H. Bukhari and K. Sarabandi, "Miniaturized Omnidirectional Horizontally Polarized Antenna," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 10, pp. 4280-4285, Oct. 2015, doi: 10.1109/TAP.2015.2456971.

[126] A. Boukarkar, X. Q. Lin, J. W. Yu, P. Mei, Y. Jiang and Y. Q. Yu, "A Highly Integrated Independently Tunable Triple-Band Patch Antenna," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2216-2219, 2017, doi: 10.1109/LAWP.2017.2707095.

[127] W. Yang, Y. Li, Q. Xue, S. Liao and W. Che, "Miniaturized Broadband Dual-Polarized Dipole Antenna Based on Multiple Resonances and its Array for Base-Station Applications," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 11, pp. 11188-11193, Nov. 2022, doi: 10.1109/TAP.2022.3209273.

[128] D. Caratelli, R. Cicchetti, V. Cicchetti and O. Testa, "A Wideband High-Gain Circularly-Polarized Dielectric Horn Antenna Equipped With Lamé-Axicon Stacked-Disk Lens for Remote Sensing, Air Traffic Control and Satellite Communications," in IEEE Access, vol. 11, pp. 20912-20922, 2023, doi: 10.1109/ACCESS.2023.3249114.

[129] C. Milias et al., "Metamaterial-Inspired Antennas: A Review of the State of the Art and Future Design Challenges," in IEEE Access, vol. 9, pp. 89846-89865, 2021, doi: 10.1109/ACCESS.2021.3091479.

[130] S. A. H. Saghanezhad and Z. Atlasbaf, "Miniaturized Dual-Band CPW-Fed Antennas Loaded With U-Shaped Metamaterials," in IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 658-661, 2015, doi: 10.1109/LAWP.2014.2376554.

[131] L. Zhu, Z. J., X. Xiao, D. O. Wu and X. -G. Xia, "3-D Beamforming for Flexible Coverage in Millimeter-Wave UAV Communications," IEEE Wireless Communications Letters, vol. 8, no. 3, pp. 837-840, June 2019.

[132] A. Simonsson, S. O. Petersson and G. Widell, "Dual Polarization Beamforming Coverage Demonstrated with 5G NR SSB," in 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Helsinki, Finland, 2021.

[133] X. Cao, S. Yan and M. Peng, "mmWave-based Beamforming for Capacity Maximization in UAV-Aided Maritime Communication Networks," in IEEE/CIC International Conference on Communications in China, Xiamen, China, 2021.

[134] M. D. Zakaria, D. Grace and P. D. Mitchhell, "Antenna Array Beamforming Strategies for High Altitude Platform and Terrestrial Coexistance Using K-Means Clustering," in IEEE Malaysia Internatinal Conference on Communications (MICC), Johor Bahru, Malaysia, 2017.

[135] E. Juan, M. Lauridsen, J. Wigard and P. Mogensen, "Performance Evaluation of the 5G NR Conditional Handover in LEO-based Non-Terrestrial Networks," 2022 IEEE Wireless Communications and Networking Conference (WCNC), Austin, TX, USA, 2022, pp. 2488-2493

[136] Bernard Sklar, Fredric J. Harris, " Digital Communications: Fundamentals and Applications ", 3rd Edition, Pearson, July 2021.

[137] Lin, Xingqin, et al. "5G from space: An overview of 3GPP non-terrestrial networks." IEEE Communications Standards Magazine, (2021): 147-153.

[138] Perez-Neira, A. I., Vazquez, M. A., Shankar, M. B., Maleki, S., & Chatzinotas, S. (2019). Signal processing for high-throughput satellites: Challenges in new interference-limited scenarios. IEEE Signal Processing Magazine, 36(4), 112-131.

[139] Angeletti, Piero & De Gaudenzi, Riccardo & Lisi, Marco. (2008). From "Bent Pipes" to "Software Defined Payloads": Evolution and Trends of Satellite Communications Systems. Proceedings of the 26th AIAA International Communications Satellite Systems Conference. 1-10. 10.2514/6.2008-5439.

[140] T. M. Braun, “Satellite Communications: Payload and System”. Wiley-IEEE Press, 2012.

[141] Angeletti, Piero & Alagha, Nader. (2009). Space/ground beamforming techniques for emerging hybrid satellite terrestrial networks. 27th International Communications Satellite Systems Conference (ICSSC 2009), Edimburgh, UK. 1. 10.1049/cp.2009.1162.

[142] E. Axell, G. Leus, E. G. Larsson and H. V. Poor, "Spectrum Sensing for Cognitive Radio : State-of-the-Art and Recent Advances," in IEEE Signal Processing Magazine, vol. 29, no. 3, pp. 101-116, May 2012, doi: 10.1109/MSP.2012.2183771.

[143] H. B. Yilmaz, T. Tugcu, F. Alagöz and S. Bayhan, "Radio environment map as enabler for practical cognitive radio networks," in IEEE Communications Magazine, vol. 51, no. 12, pp. 162-169, December 2013, doi: 10.1109/MCOM.2013.6685772.

[144] E. Lagunas, S. K. Sharma, S. Maleki, S. Chatzinotas and B. Ottersten, "Resource Allocation for Cognitive Satellite Communications With Incumbent Terrestrial Networks," in IEEE Transactions on Cognitive Communications and Networking, vol. 1, no. 3, pp. 305-317, Sept. 2015, doi: 10.1109/TCCN.2015.2503286.

[145] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas and S. Chatzinotas, "A Survey on Nongeostationary Satellite Systems: The Communication Perspective," in IEEE Communications Surveys & Tutorials, vol. 25, no. 1, pp. 101-132, Firstquarter 2023, doi: 10.1109/COMST.2022.3197695.

[146] Weerackody, Vijitha & Cuevas, and Enrique, “Technical Challenges and Performance of Satellite Communications on-the-Move Systems”, Johns Hopkins Apl Technical Digest, 2011.

[147] Dala Pegorara Souto V, Dester PS, Soares Pereira Facina M, Gomes Silva D, de Figueiredo FAP, Rodrigues de Lima Tejerina G, Silveira Santos Filho JC, Silveira Ferreira J, Mendes LL, Souza RD, Cardieri P. Emerging MIMO Technologies for 6G Networks. Sensors (Basel). 2023 Feb 8;23(4):1921. doi: 10.3390/s23041921. PMID: 36850518; PMCID: PMC9961246.

[148] Y. Pan, K. Wang, C. Pan, H. Zhu and J. Wang, "UAV-Assisted and Intelligent Reflecting Surfaces-Supported Terahertz Communications," in IEEE Wireless Communications Letters, vol. 10, no. 6, pp. 1256-1260, June 2021, doi: 10.1109/LWC.2021.3063365.

[149] Huo, Y., Lin, X., Di, B., Zhang, H., Hernando, F.J., Tan, A.S., Mumtaz, S., Demir, O.T., & Chen-Hu, K. (2023). Technology Trends for Massive MIMO towards 6G. *ArXiv, abs/2301.01703*.

[150] W. Mei, B. Zheng, C. You and R. Zhang, "Intelligent Reflecting Surface-Aided Wireless Networks: From Single-Reflection to Multireflection Design and Optimization," in Proceedings of the IEEE, vol. 110, no. 9, pp. 1380-1400, Sept. 2022, doi: 10.1109/JPROC.2022.3170656.

[151] A. Shojaeifard et al., "MIMO Evolution Beyond 5G Through Reconfigurable Intelligent Surfaces and Fluid Antenna Systems," in Proceedings of the IEEE, vol. 110, no. 9, pp. 1244-1265, Sept. 2022, doi: 10.1109/JPROC.2022.3170247.

[152] Wang, Z., Zhang, J., Du, H., Sha, W.E., Ai, B., Niyato, D.T., & Debbah, M. (2022). Extremely Large-Scale MIMO: Fundamentals, Challenges, Solutions, and Future Directions. *ArXiv, abs/2209.12131*.

[153] S. Chen, S. Sun, G. Xu, X. Su and Y. Cai, "Beam-Space Multiplexing: Practice, Theory, and Trends, From 4G TD-LTE, 5G, to 6G and Beyond," in IEEE Wireless Communications, vol. 27, no. 2, pp. 162-172, April 2020, doi: 10.1109/MWC.001.1900307.

[154] T. Delamotte, M. G. Schraml, R. T. Schwarz, K. -U. Storek and A. Knopp, "Multi-Antenna-Enabled 6G Satellite Systems: Roadmap, Challenges and Opportunities," WSA 2021; 25th International ITG Workshop on Smart Antennas, French Riviera, France, 2021, pp. 1-6.

[155] A. Avellan and S. Jayasimha, “System and method for high throughput fractionated satellites (HTFS) for direct connectivity to and from end user devices and terminals using flight formations of small or very small satellites,” US Patent 9,973,266 B1, May 15, 2018.

[156]] F. Vidal, H. Legay, G. Goussetis, M. Garcia Vigueras, S. Tubau, and J.-D. Gayrard, “A methodology to benchmark flexible payload architectures in a megaconstellation use case,” International Journal of Satellite Communications and Networking, vol. 39, no. 1, pp. 29–46, 2021. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/sat.1344.

[157]. A. Ali, A. Mitra, and B. Aïssa, “Metamaterials and Metasurfaces: A Review from the Perspectives of Materials, Mechanisms and Advanced Metadevices,” Nanomaterials, vol. 12, no. 6, p. 1027, Mar. 2022, doi: 10.3390/nano12061027.

[158] P. S. Manage, U. Naik, S. Nargundkar and V. Rayar, "A Survey on applications of Metamaterials in Antenna Design," 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), Tirunelveli, India, 2020, pp. 153-158, doi: 10.1109/ICSSIT48917.2020.9214088.

[159] M. Alibakhshikenari et al., "A Comprehensive Survey of “Metamaterial Transmission-Line Based Antennas: Design, Challenges, and Applications”," in IEEE Access, vol. 8, pp. 144778-144808, 2020, doi: 10.1109/ACCESS.2020.3013698.

[160] J. Zhao et. al., “A tunable metamaterial absorber using varactor diodes”, 2013 New J. Phys. 15 043049.

[161] L. -X. Wu et al., "Wideband Dual-Feed Dual-Polarized Reflectarray Antenna Using Anisotropic Metasurface," in IEEE Antennas and Wireless Propagation Letters, vol. 21, no. 1, pp. 129-133, Jan. 2022, doi: 10.1109/LAWP.2021.3121018.

[162] C. Ding and K. -M. Luk, "Wideband Omnidirectional Circularly Polarized Antenna for Millimeter-Wave Applications Using Printed Artificial Anisotropic Polarizer," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 1103-1104, doi: 10.1109/APUSNCURSINRSM.2019.8888448.

[163] M. Y. Jamal, M. Li, K. L. Yeung, X. Li, L. Jiang and T. Itoh, "A Low-Profile Fabry–Pérot Cavity Antenna Using Anisotropic Metasurface," in IEEE Antennas and Wireless Propagation Letters, vol. 21, no. 2, pp. 356-360, Feb. 2022, doi: 10.1109/LAWP.2021.3131628.

[164] H. Pablo Zapata Cano, Z. D. Zaharis, T. V. Yioultsis, N. V. Kantartzis and P. I. Lazaridis, "Pattern Reconfigurable Antennas at Millimeter-Wave Frequencies: A Comprehensive Survey," in IEEE Access, vol. 10, pp. 83029-83042, 2022, doi: 10.1109/ACCESS.2022.3196456.

[165] M. U. Afzal and K. P. Esselle, ``Steering the beam of medium-to-high gain antennas using near-field phase transformation,'' IEEE Trans. Antennas. Propag., vol. 65, no. 4, pp. 16801690, Apr. 2017.

[166] Q.-Y. Guo and H. Wong, ``Wideband and high-gain Fabry-Pérot cavity antenna with switched beams for millimeter-wave applications,'' IEEE Trans. Antennas Propag., vol. 67, no. 7, pp. 4339-4347, Jul. 2019

[167] Y. -X. Wang, X. -J. Wu, Z. Chen and T. Yuan, "A Radiation Pattern-Reconfigurable Antenna with Water and Anisotropic Materials," 2021 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Chongqing, China, 2021, pp. 145-147, doi: 10.1109/IMWS-AMP53428.2021.9643985.

[168] F. Yang and Y. Rahmat-Samii, Electromagnetic Band Gap Structure in Antenna Engineering. Cambridge, U.K.: Cambridge Univ. Press, 2008]. In [I. Ben Mabrouk, M. Al-Hasan, M. Nedil, T. A. Denidni and A. -R. Sebak, "A Novel Design of Radiation Pattern-Reconfigurable Antenna System for Millimeter-Wave 5G Applications," in IEEE Transactions on Antennas and Propagation, vol. 68, no. 4, pp. 2585-2592, April 2020, doi: 10.1109/TAP.2019.2952607.

[169] P. M. T. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo and S. A. Tretyakov, "Magnetodielectric Substrates in Antenna Miniaturization: Potential and Limitations," in IEEE Transactions on Antennas and Propagation, vol. 54, no. 11, pp. 3391-3399, Nov. 2006, doi: 10.1109/TAP.2006.884303.

[170] M. Mirzaee and Y. Kim, "Conformal Miniaturized Antenna with Enhanced Bandwidth and Efficiency Using Periodic Magneto-Dielectric Anisotropic Meta-Substrate," 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI), Singapore, Singapore, 2021, pp. 1075-1076, doi: 10.1109/APS/URSI47566.2021.9703811.

[171] N. R. Babu, H. B. Joshi, A. Gahlaut, S. Shah, R. Kumar and A. R. Tanna, "Transmission characteristics of Plasma-based microwave absorbing panel in Near and Far field region of testing antenna," 2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON), Bangalore, India, 2022, pp. 572-576, doi: 10.1109/MAPCON56011.2022.10047775.

[172] R. Panwar, S. Puthucheri and D. Singh, "Experimental Demonstration of Novel Hybrid Microwave Absorbing Coatings Using Particle-Size-Controlled Hard–Soft Ferrite," in IEEE Transactions on Magnetics, vol. 54, no. 11, pp. 1-5, Nov. 2018, Art no. 2002605, doi: 10.1109/TMAG.2018.2828782.

[173] F. He, K. Si, L. Chen, L. Xiao and J. Jiang, "Anisotropic Absorbing Honeycomb and FSS Composite Structure for Curved Broadband RCS Reduction," 2022 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Guangzhou, China, 2022, pp. 1-3, doi: 10.1109/IMWS-AMP54652.2022.10106923.

[174] P. Zhang and J. Li, "Compact UWB and Low-RCS Vivaldi Antenna Using Ultrathin Microwave-Absorbing Materials," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1965-1968, 2017, doi: 10.1109/LAWP.2017.2690670.

[175] A. V. Gevorkyan and P. T. Yu, "The Radiation Characteristics of 3.43:1 Bandwidth Dipole Antenna with Radar Absorbing Material," 2018 IEEE Radio and Antenna Days of the Indian Ocean (RADIO), Wolmar, Mauritius, 2018, pp. 1-2, doi: 10.23919/RADIO.2018.8572346.

[176] ISO/ASTM 52900:2015: “Additive Manufacturing – General Principles – Terminology”, URL: https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en . Last accessed: 27 June 2023.

[177] K. Johnson et al., "Digital Manufacturing of Pathologically-Complex 3D Printed Antennas," in IEEE Access, vol. 7, pp. 39378-39389, 2019, doi: 10.1109/ACCESS.2019.2906868.

[178] N. Chudpooti, G. Savvides, N. Duangrit, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Harmonized Rapid Prototyping of Millimeter-Wave Components Using Additive and Subtractive Manufacturing," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 12, no. 7, pp. 1241-1248, July 2022, doi: 10.1109/TCPMT.2022.3181886.

[179] E. García-Marín, J. L. Masa-Campos, P. Sánchez-Olivares and J. A. Ruiz-Cruz, "Evaluation of Additive Manufacturing Techniques Applied to Ku-Band Multilayer Corporate Waveguide Antennas," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 11, pp. 2114-2118, Nov. 2018, doi: 10.1109/LAWP.2018.2866631.

[180] H. Kähkönen, S. Proper, J. Ala-Laurinaho and V. Viikari, "Comparison of Additively Manufactured and Machined Antenna Array Performance at Ka-Band," in IEEE Antennas and Wireless Propagation Letters, vol. 21, no. 1, pp. 9-13, Jan. 2022, doi: 10.1109/LAWP.2021.3113372.

[181] S. Mufti, A. Tennant, L. Seed and C. J. Smith, "Efficiency measurements of additive manufactured electrically small antennas," 2017 International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT), Athens, Greece, 2017, pp. 347-349, doi: 10.1109/IWAT.2017.7915397.

[182] G. Mitchell, T. Anthony, Z. Larimore and P. Parsons, "Antenna Comparison for Additive Manufacturing versus Traditional Manufacturing Methods," 2021 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), Boulder, CO, USA, 2021, pp. 3-4, doi: 10.23919/USNC-URSINRSM51531.2021.9336492.

[183] Liu, P., & Chen, Z. N. (2022). Beam-Scanning Metalens Antenna using Prior-Knowledge-Guided Machine-Learning-Based Synthesis. *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, AP-S/URSI 2022 - Proceedings*, 435–436. https://doi.org/10.1109/AP-S/USNC-URSI47032.2022.9886691

[184] di Renzo, M., Zappone, A., Debbah, M., Alouini, M. S., Yuen, C., de Rosny, J., & Tretyakov, S. (2020). Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and the Road Ahead. *IEEE Journal on Selected Areas in Communications*, *38*(11), 2450–2525. https://doi.org/10.1109/JSAC.2020.3007211.

[185] H. M. T. N. a. S. K. A. K. El Misilmani, "A review on the design and optimization of antennas using machine learning algorithms and techniques," 2020.

[186] J. V. A. G. a. C. C. O. Noakoasteen, "Antenna Design Using a GAN-Based Synthetic Data Generation Approach," 2022.

[187] Z. W. e. al., "Automated Antenna Design via Domain Knowledge-Informed Reinforcement Learning and Imitation Learning," 2023.

[188] H. M. T. N. a. S. K. A. K. El Misilmani, "A review on the design and optimization of antennas using machine learning algorithms and techniques," 2020.

[189] T. K. Z. a. E. H. Zhang, "Data-driven machine learning techniques for self-healing in cellular wireless networks: Challenges and solutions," 2022.

[190] S. B. R. e. a. Tirmizi, "Hybrid Satellite–Terrestrial Networks toward 6G: Key Technologies and Open Issues," 2022.

[191] "Shared Access Terrestrial-Satellite Backhaul Network Enabled by Smart Antennas," [Online]. Available:https://wwwfr.uni.lu/snt/research/sigcom/projects/sansa_shared_access_terrestrial_satellite_backhaul_network_enabled_by_smart_antennas. [Accessed 21 06 2023].

[192] "Satellite and Terrestrial Network for 5G," [Online]. Available: https://5g-ppp.eu/sat5g/. [Accessed 21 06 2023].

[193] "5G Communication with a Heterogeneous, Agile Mobile network in the Pyunchang Winter Olympic Competion," [Online]. Available: https://www.5g-champion.eu/. [Accessed 21 06 2023].

[194] "5G AgiLe and Flexible Integration of Satellite and Cellular," [Online]. Available: https://5g-allstar.eu/. [Accessed 21 06 2023].

[195]"Hybrid Networks for Global Internet Access," [Online]. Available: https://cordis.europa.eu/project/id/867018. [Accessed 21 06 2023].

[196] L. M. B. a. D. G. A. Ahmed, "Enabling vertical han- dover decisions in heterogeneous wireless networks: A state-of-the-art and a classification," 2014.

[197] N. P. L. M. a. C. V. D. Xenakis, "Mobility man- agement for femtocells in LTE-advanced: Key aspects and survey of handover decision algorithms," 2014.

[198] M. A. a. W. I. P. K. Chowdhury, "Handover schemes in satellite networks: State-of-the-art and future research directions," 2006.

[199] F. P. R. D. a. A.-L. B. M. Crosnier, "Handover management optimization for LTE terrestrial network with satellite backhaul," 2011.

[200] X. Li, W. Feng, J. Wang, Y. Chen, N. Ge and C.-X. Wang, "Enabling 5G on the Ocean: A Hybrid Satellite-UAV-Terrestrial Network Solution," 2020.

[201] Y. Wang, W. Feng, J. Wang and T. Quek, "Hybrid Satellite-UAV-Terrestrial Networks for 6G Ubiquitous Coverage: A Maritime Communications Perspective," 2021.

[202] X. Li, W. Feng, Y. Chen, C.-X. Wang and N. Ge, " Maritime Coverage Enhancement Using UAVs Coordinated With Hybrid Satellite-Terrestrial Networks," 2020.

[203] J. Ye, S. Dang, B. Shihada and M.-S. Alouini, "Space-Air-Ground Integrated Networks: Outage Performance Analysis," 2020.

[204] M. Hosseinian, "Review of 5G NTN Standards Development and Technical Challenges for Satellite Integration With the 5G Network," vol. 34141, doi: 10.1109/MAES.2021.3072690.

[205] Y. Qi, H. Deng, M. Liu, and Z. Li, "On the standardization of key enabling technologies in non-terrestrial network air-interface design," 2021 IEEE/CIC International Conference on Communications in China, ICCC Workshops 2021, pp. 343–348, Jul. 2021, doi: 10.1109/ICCCWORKSHOPS52231.2021.9538924.

[206] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks," IEEE Communications Standards Magazine, vol. 5, no. 4, pp. 147–153, Dec. 2021, doi: 10.1109/MCOMSTD.011.2100038.

[207] M. Giordani and M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," IEEE Netw, vol. 35, no. 2, pp. 244–251, Mar. 2021, doi: 10.1109/MNET.011.2000493.

[208] 3GPP, "3GPP TR 38.811, 'Study on New Radio (NR) to support non-terrestrial networks (Rel-15),'" Sep. 2020.

[209] "3GPP TR 38.901, 'Study on channel model for frequencies from 0.5 to 100 GHz' (Rel-16)," Mar. 2017.

[210] "3GPP TR 38.821, "Solutions for NR to support non-terrestrial networks(NTN) (Rel-16)"," May 2021.

[211] "3GPPP TR 23.737, 'Study on architecture aspects for using satellite access in 5G' (Ref-16)," Jun. 2018.
[212] A. Guidotti et al., "The path to 5G-Advanced and 6G Non-Terrestrial Network systems," 2022 11th Advanced Satellite Multimedia Systems Conference and the 17th Signal Processing for Space Communications Workshop, ASMS/SPSC 2022, 2022, doi: 10.1109/ASMS/SPSC55670.2022.9914764.

[213] J. Capmany and D. Novak, "Microwave photonics combines two worlds," Nature Photonics 2007 1:6, vol. 1, no. 6, pp. 319–330, Jun. 2007, doi: 10.1038/nphoton.2007.89.

[214] D. Marpaung, J. Yao, and J. Capmany, "Integrated microwave photonics," Nature Photonics 2019 13:2, vol. 13, no. 2, pp. 80–90, Jan. 2019, doi: 10.1038/s41566-018-0310-5.

[215] S. Pan et al., “Satellite Payloads Pay off,” IEEE Microw Mag, vol. 16, no. 8, pp. 61–73, Sep. 2015, doi: 10.1109/MMM.2015.2441619.

[216] P. Shilong, Z. Dan, and Z. Fangzheng, “Microwave Photonics for Modern Radar Systems,” Transactions of Nanjing University of Aeronautics & Astronautics, vol. 31, no. 3, pp. 219–240, 2014, Accessed: Jun. 19, 2023. [Online]. Available: http://tnuaa.nuaa.edu.cn/njhkhten/article/abstract/201403001

[217] L. Wille Ng and A. A. Walston, “The First Demonstration Of An Optically Steered Microwave Phased Array Antenna Using True-Time-Delay,” Journal of Lightwave Technology, vol. 9, no. 9, pp. 1124–1131, 1991, doi: 10.1109/50.85809.

[218] C. Tsokos et al., “True Time Delay Optical Beamforming Network Based on Hybrid Inp-Silicon Nitride Integration,” Journal of Lightwave Technology, Vol. 39, Issue 18, pp. 5845-5854, vol. 39, no. 18, pp. 5845–5854, Sep. 2021, doi: 10.1109/JLT.2021.3089881.

[219] P. Zheng et al., “A wideband 1×4 optical beam-forming chip based on switchable optical delay lines for Ka-band phased array,” Opt Commun, vol. 488, Jun. 2021, doi: 10.1016/J.OPTCOM.2021.126842.

[220] G. K. Gopalakrishnan, W. K. Burns, and C. H. Bulmer, “Microwave-Optical Mixing in LiNb03 Modulators,” IEEE Trans Microw Theory Tech, vol. 41, no. 12, pp. 2383–2391, 1993, doi: 10.1109/22.260732.

[221] M. E. Manka, “Microwave photonics for electronic warfare applications,” 2008 IEEE International Meeting on Microwave Photonics jointly held with the 2008 Asia-Pacific Microwave Photonics Conference, MWP2008/APMP2008, pp. 275–278, 2008, doi: 10.1109/MWP.2008.4666690.

[222] R. W. Boyd, “Nonlinear Optics, Third Edition,” Nonlinear Optics, Third Edition, pp. 1–613, Jan. 2008.

[223] T. Kawanishi, “Electro-optic Modulation for Photonic Networks,” 2022, doi: 10.1007/978-3-030-86720-1.

[224] H. Lu et al., “Optical frequency comb based multi-band microwave frequency conversion for satellite applications,” Optics Express, Vol. 22, Issue 1, pp. 869-877, vol. 22, no. 1, pp. 869–877, Jan. 2014, doi: 10.1364/OE.22.000869.

[225] M. Sotom, B. Benazet, A. Le Kernec, and M. Maignan, “Microwave Photonics Technologies for Flexible Satellite Payloads,” 2009.