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Roadmap paper

Antenna Systems for Satellite Communication Terminals

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Abstract
This Roadmap presents the research trends on antenna systems for Satellite Communication terminals. To address the challenges posed by this application in terms of wide fractional bandwidth and large field-of-view, several antenna concepts and architectures are being investigated, which can be grouped in three main technology areas: fully electronic scan, fully mechanical scan with unconventional steering mechanisms and beam switching. Design techniques, current results and future developments are outlined, considering representative examples for each technology area.

Key terms
Phased array antenna; lens antenna; reflectarray; transmitarray; continuous transverse stub antenna; optical beamforming; satellite communications, scanning antennas; mobile terminals.

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1. Introduction

SATellite COMmunications (SATCOM) terminals, originally developed to provide internet connectivity in isolated areas with limited terrestrial network infrastructure, are becoming an essential element of future communication architectures. Next to the connection to remote fixed sites, SATCOM antenna systems are being used to support connectivity and communication to users located on moving platforms, such as boats, trains and aircrafts, through the so-called Satcom-On-The-Move (SOTM) terminals.

The tremendous increase in data rate thanks to the deployment of High Throughput Satellites, particularly in Geostationary Orbit (GEO), together with the proliferation of Low (LEO) and Medium (MEO) Earth Orbit (the so called NGEO) satellite constellations, aimed at providing continuity and more flexibility in coverage, have dramatically improved the reliability of SATCOM services.

The main challenge for the design of SATCOM antenna systems consists in balancing the trade-off between the demanding RF performance in terms of wide fractional bandwidth and large field-of-view, in combination with dual polarisation with strong polarisation discrimination, and the need of cost effective solutions. To lower the price of SATCOM-based services and increase their attractiveness with respect to their terrestrial counterparts, innovations are needed in terms of antenna concepts, semiconductor technology and antenna system architecture. Moreover, the increase in operating frequency, currently in the Ku and K/Ka-bands, but moving upwards, pushes for a higher integration grade between the antenna and the transmit and receive electronics, and requires low loss materials, and accurate and affordable manufacturing and assembly processes. This roadmap sketches the main research trends on these technical areas.

1.1. Roadmaps in detail

The roadmap is organised in three sections corresponding to three main approaches to beam steering:

1.1.1. Fully electronic scan

Vigano presents current developments and main opportunities for active array antennas with analogue beamforming from an industrial perspective. *Aslan* and *Roederer* discuss implementation challenges and performance trade-offs in multiple beam generation for various (analogue, digital, hybrid) active array antenna architectures. *Zhou* describes main trends on reflectarray technology for SATCOM terminals. *Clemente* and *Sauleau* present the design principles of passive and programmable transmitarrays and the future developments foreseen for SOTM applications. *González Ovejero* discusses potentialities and challenges of solutions based on electronically reconfigurable Metasurfaces (MTSs). *Boccia* and *Arnieri* outline main trends in packaging and assembly technologies for antenna integration.

1.1.2. Fully mechanical scan

Ettorre and *Foglia Manzillo* elaborate on the benefit and emerging challenges of continuous transverse stub antennas for SATCOM terminals. *Della Giovampaola* and *Matos* present scanning antenna architectures based on rotating/translating lenses.

1.1.3. Beam switching

Lassauce and *Ettorre* outline the advantages and potential of quasi-optical beamformers on the basis of three key examples.

Active Array Antennas for SATCOM

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The need for SATCOM arrays Communications relying on satellite connection are becoming more and more a commodity. In the past, these communication links were seen as the last resort, to be used only when any other type of connection was not present or failed. With the help of High Throughput Satellites (HTS), the cost of services based on satellite connection became lower, in some cases comparable to terrestrial solutions. The future of SATellite COMmunications (SATCOM), for fixed and mobility applications, looks bright and interesting enough that many large companies like Amazon or SpaceX are investing on this.

Historically, connections for Geostationary Equatorial Orbit (GEO) satellite communications were enabled thanks to reflector antennas. For fixed applications, the installation of this kind of terminals is as simple as a one time carefully pointing the antenna toward the GEO satellite position. Differently, for on-the-move applications, the reflector is mechanically pointed with to 2 or 3 axis motors.

Nowadays, with the advent of many lower orbit constellations, more complexity in the connectivity systems is required. Even for fixed installations, the antenna needs to track the satellite and to perform hand-overs between setting and raising satellites. This is contributing to a wider adoption of active phased array antennas, whose technical characteristics are a perfect match for these new scenarios.

Indeed, the capabilities of array antennas for quickly changing the beam direction without any physical movement of the terminal, as well as the possibility of fast switching or even dual beam, are fundamental for on-the-move applications and even for fixed ones when connecting to Non Geostationary Orbit (NGSO) constellations.

Current status and examples of active phased arrays for SATCOM Analogue active arrays are, at the moment, the type of active array antennas mostly available on the market. An example of this type of architecture is given in Fig. 1 for transmission (TX). Having both amplitude and phase control at element level allows for the possibility of shaping the pattern in the most accurate way with respect to other architectures where only phase control is available. Performances in this kind of arrays are dictated by the element design, the behavior of the Integrated Circuit (IC) where the amplification and phase shifting functions are implemented, and their integration.

Regarding the element efficiency, values in the order of 85 % are commonly achieved depending on the width of the frequency band required and other essential parameters like the polarization purity. These elements are usually implemented in Printed Board Circuit (PCB) technology. Since the amplification in this type of array is really close to the element, it is less important to have a quasi-lossless Beam Forming Network (BFN). For this reason, PCBs are one of the most preferred option to implement the complete array. In this way, the radiating element, the BFN and the IC hosting board with power and control distribution can all be done on the same substrate employing the same core technology. Hybrid approaches where the elements and/or the BFN are done in waveguide technology are also considered, especially when a second level of amplification is not foreseen. The use of lenses in combination with active phased array can be exploited in order to increase performances at difficult pointing angles [1] or to reduce the number of active components needed for a given scan angle.

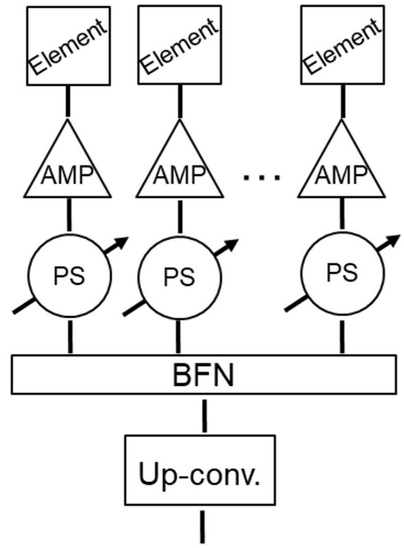

Figure 1: Possible architecture for a TX active analogue array.

For what concerns the IC or MMIC (Monolithic Microwave Integrated Circuits), performances are dictated by the technology chosen for the implementation. Depending on the technology, indeed, different Noise Figures (NF) in reception and radiofrequency (RF) output power in transmission can be achieved. Low Noise Amplifiers (LNA) in GaAs (Gallium Arsenide) can provide a NF as low as 0.4 dB while less expensive technologies are usually in the range of 2-3 dB. In the same way GaAs and Gallium Nitride (GaN) technology can usually provide more power output (easily up to a few watts) with respect to Silicon based MMICs where numbers are more in the order of tens of dBm. Since in active arrays many MMICs are used at the same time, and cost is still the main limitation for a large adoption, the use of Silicon based technology is advancing and, for most of the applications, replacing GaAs and GaN options [2].

Finally, having an antenna element and the MMIC designed to work together usually brings large advantages. This is unfortunately not so common since array development companies are most of the time focusing on the radiating part and resorting for the electronic components to what is available on the market.

Several examples of terminals based on this architecture type are present on the market. Most of them, like Viasat [3], Requtech and Ball ones, are based on modular building blocks and can be scaled up or down depending on the needs.

This modularity choice was taken for two main reasons. The first one is the flexibility for addressing markets with different performance needs. The second one is the ability to assemble larger units when a single physical PCB is not large enough to provide adequate performances for the specific application.

Some cases have been mainly designed for mobility as the Rockwell Collins K_u terminal or the Viasat aero terminals, illustrated in Fig. 2. For this reason, they are already targeting a large scan angle and sometimes already include the possibility of creating two beams for Make Before Break (MBB).

Figure 2: Examples of active phased array antennas for fixed and mobile applications (courtesy of Viasat).

Looking into the future of active phased arrays In order to answer to the ever growing need for more capacity, a shift towards higher frequencies is expected in the long term. This already happened in the past when SATCOM frequencies moved from L and S bands towards K_u and K_a. In the future, K_a frequency band and higher ones are expected to be used to achieve broadband communications. For the same reason, a large instantaneous bandwidth should be targeted for maximising the capacity and, in this way, the bandwidth economics.

The expectation from the SATCOM market regarding future antennas is that they will be compact, efficient and possibly able to connect to several different constellations. This could mean then to be capable to cover different frequencies in a small form factor terminal. Nowadays, depending on which frequencies needs to be covered, the most efficient way to achieve super large bands may actually be to address the need with different, separated antennas. The advantage of separated apertures is also the possibility to easily operate both of them at the same time. Indeed, if a large band antenna design was available where performances are close to the ones of the separated version, an indisputable advantage in terms of size could be achieved. Another aspect mentioned in the previous section is the capability to connect to different satellites (even in the same frequency band) at the same time. If the number of beams needed is reduced, an analogue active array approach can be used, for example, by partitioning the aperture into several 'independent' antennas, or by adding an extra BFN or even by implementing a fast time switching. When the number of beams is larger instead, the most efficient way to achieve this capability is to resort to a digital phased array.

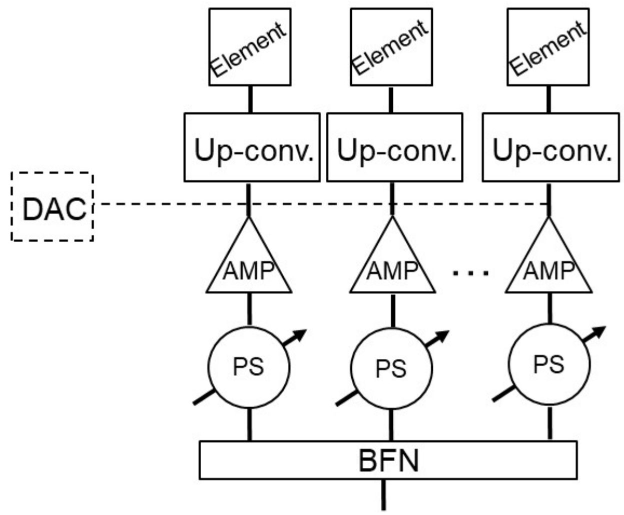

Figure 3: Example of digital array configuration (TX).

At the moment, the power consumption of these kind of architectures (as the one depicted in Fig. 3 as an example) is still quite demanding for many applications, especially for on-the-move platforms. In the long term , the expectation is, for many of the components needed in this case, to increase their efficiency and become less and less power hungry. A complete digital approach at element level, with a radiating aperture covering a large frequency band, is possibly the answer to many of the market needs, provided a lost-cost low-power implementation can be proposed.

Conclusion The need for affordable and efficient active phased arrays is today becoming more and more clear, thanks to the advent of many satellite constellations. In order to have terminals based on this technology becoming widely spread, a significant effort has to be spent on making these solutions more power efficient and affordable. Furthermore, covering larger frequency bands and being able to guarantee a seamless handover between satellites are key to the success of the discussed technology in the coming years.

Multiple Beam Forming Schemes for User Terminal Antennas: Now and Next

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Introduction Low Earth Orbit (LEO) satellite constellations for broadband Internet access, such as TeleSat, Starlink, Amazon Kuiper and OneWeb, are being deployed at centimeter wavelength frequencies [4]. They require highly directive and low-cost Internet user terminals with permanent beam agility over a wide field-of-view to track a satellite and, after minutes, hand-over to the next one with minimal disruption of the communications [5]. For fast Internet and no break in communication during the re-pointing of the antenna beam, stabilizing, and synchronizing with a new satellite, or to communicate with multiple satellites for improved diversity, throughput and reliability, at least two non-interfering receive links (two antenna beams) are required at the terminals [6]. This is not only useful for LEO Internet, but also for aircraft user terminals for Geostationary Equatorial Orbit (GEO) satellites [7]. Generating multiple beams is important to simultaneously connect to LEO and GEO and to integrate satellite communications with the terrestrial networks for 5G and beyond [8].

The technical solutions towards designing such ambitious user antennas are diverse. Various types of candidates range from traditional multiple mechanically-driven parabolas, to mechanical control combined with electronic scanning or switching, and to modern fully electronic control [9]. Among all options, the use of large (i.e. with hundreds of radiating elements) active phased arrays with full electronic control is seen as the ultimate goal, since they provide the most flexible and versatile multiple beam forming capability [10]. At the same time, low-cost is key for the industry. This makes planar printed antennas with silicon-based radio frequency (RF) and processing integrated circuits (ICs) the most suitable candidates [11].

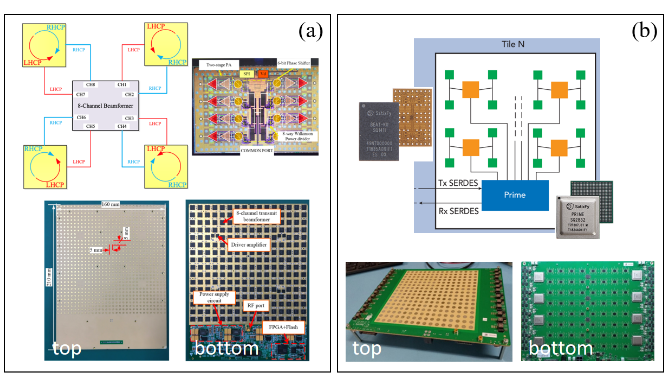

Figure 4: Recent examples of user terminal phased arrays for satellite communications: (a) a Ka-band dual circularly polarized analog array [12], (b) a Ku-band digital multi-beam array [13].

Two recent representative examples are provided in Fig. 4. Fig. 4a shows a 1024-element dual circularly polarized transmit (Tx) phased array fed by the 8-channel analog beam former ICs and realizing 2 beams via 2 orthogonal polarizations [12]. Fig. 4b shows a 256-element single polarized (arbitrary linear or circular) half-duplex transmit-receive (Tx-Rx) phased array controlled digitally by Serializer/Deserializer (SerDes) chained Prime ICs realizing up to 32 simultaneous beams [13]. While analog beam forming is only compatible with a moderate number of beams per polarization due to the component requirements, the digital beam forming case requires hundreds of converter chains, with excessive processing complexity and power consumption, which is not yet compatible with most communication systems. To find a balance, hybrid analog/digital beam forming strategies are also proposed [14]. In fact, it remains an open challenge to develop innovative ways to simplify the front-end architecture in active multiple beam phased arrays, without compromising much on the beam forming performance.

In this roadmap contribution, the existing and emerging challenges in multiple beam generation are explained by discussing various types of beam forming schemes. This knowledge is applied to establish future research directions.

Challenges in Multibeam Generation Five characteristic multibeam phased array architectures are illustrated in Fig. 5. The schemes use one-dimensional arrays for simplicity, yet they can be generalized to planar arrays. Besides, only regular antenna layouts are considered, but non-uniform (sub-)array configurations/sizes, irregular sub-array clustering/tiling or overlapped subarrays [15] can be used for radiation pattern performance improvements in terms of grating/side lobes, at the expense of increased feed network complexity. Fig. 5 focuses on the Rx architectures. Depending on the operating frequencies, Tx/Rx arrays can be on separate apertures or in common aperture for more compact design (as publicized by Amazon in Kuiper) with shared (possibly dual- or wide-band) Tx-Rx elements or interleaved individual Tx-Rx elements [16]. Next, the potential, limitations and challenges in each architecture are discussed.

T-1: analog, individual subarrays has the simplest architecture among all. Different subarrays can steer different beams in different directions and be assigned to different tasks. Beam resolution is low at least on one axis of radiation since only a portion of the array (subarray) is dedicated to a particular beam. Wide beams lead to interference problems, especially for satellites within the beam-width. Total array size and costs must increase significantly to satisfy similar per beam gain as compared to the architectures using all antenna elements for each beam.

T-2: analog, fully-connected array has a dedicated analog beam forming network for each beam. Beam forming flexibility is high due to individual element controls for all beams. This allows high beam resolution, large field-of-view and full degree-of-freedom for pattern shaping or interference mitigation. Complexity and losses in RF signal combining and component insertions grow fast with the number of beams. From this point-of-view, T-2 is the most appealing with low number of elements and/or low number of beams.

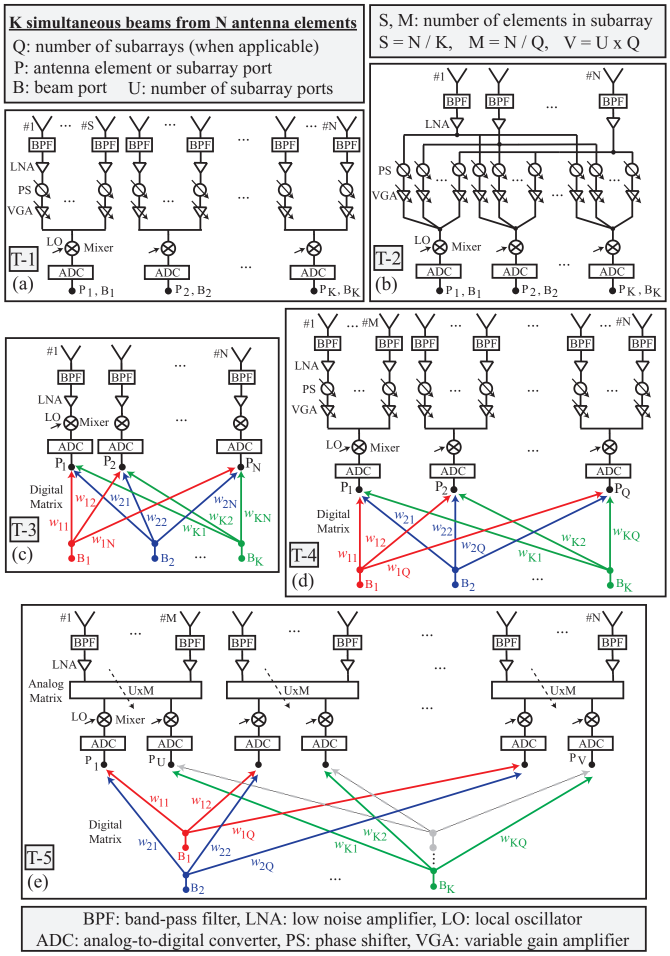

Figure 5: Various types of multi-beam Rx phased array topologies: (a) T-1: analog, individual subarrays, (b) T-2: analog, fully-connected, (c) T-3: fully-digital, (d) T-4: hybrid, single-beam subarrays, (e) T-5: hybrid, multi-beam subarrays.

T-3: fully-digital array has high beam forming flexibility as T-2, and constant analog complexity with the number of beams. Beam squint free wideband signal reception in a large field-of-view is achieved readily by adjusted time delays. Cost and digital processing complexity are the highest among all due to increasing number of signal chains with converters and mixers (as many as the number of elements). Some processing techniques for interference mitigation (which could involve computationally expensive matrix inversions) may be prohibitive for large number of beams and elements [17].

T-4: hybrid array of single-beam subarrays reduces the number of converters and mixers (thus cost, power consumption and processing burden) by grouping them at the subarray level, and allows digital sub-array time delay to reduce scan dependence with frequency. T-4 was originally used in radar for single beam operation in which every element in each single-beam subarray is optimally weighted. However, in the multibeam mode, as multiple beams are formed within the subarray beam, the field-of-view becomes limited by the beam pattern of the subarrays. The subarrays can be arranged on a linear or a planar lattice depending on the requirements. Array of linear subarrays can assign analog/digital beam forming in elevation/azimuth or vice-versa [18]. In case of planar arrangements, large spacing between the subarrays may cause unwanted grating lobes in the field-of-view. The reconfigurable subarrays can be simplified via fixed analog beam forming for a particular pattern shape or look angle definition [18].

T-5: hybrid array of multi-beam subarrays addresses the narrow field-of-view problem in T-4 by making use of multi-beam subarrays [19]. Circuit-type beam forming matrices [20] can be integrated with the subarrays having a few digitally controlled beam ports. Reconfigurability in the matrix may help cancel the grating lobes in planar arrangements. Increasing the subarray size and/or the number of beams per subarray results in larger implementation complexity and insertion losses.

Future Research Lines To make an optimal decision on the beam forming architecture for given requirements, novel interdisciplinary goal functions integrating power consumption, link budget and cost criteria should be derived. Power consumption modeling in multibeam antennas is particularly intriguing as it has been recently shown that there is an optimal number of array elements in terms of total power consumption, and that the fully digital architecture does not necessarily consume more power than the analog or hybrid architectures [21].

Among all the multibeam array architectures presented in the paper, the hybrid scheme in T-5 is very promising with its relatively high radiation pattern performance and low analog/digital implementation complexity. Although conceptually discussed [22] and implemented in radio astronomical phased arrays [23], multibeam subarrays are not yet adopted in satellite terminals. The main research question here is: “What are the key features, advantages, performances, and limitations of the multibeam subarrays in user terminal antennas and what innovative solutions can enhance their applicability?”

To answer this question, future research should focus on: (i) reducing the complexity and losses in reconfigurable analog multibeam antenna feed circuits, (ii) increasing the number of subarray beams with reasonable complexity, (iii) maintaining radiation properties (beam directions, gains, side lobe levels) over a wide field-of-view and bandwidth under practical design factors such as antenna coupling, (iv) obtaining low-cost IC-based designs with modularity and scalability.

Conclusion The benefits of generating multiple beams at modern satellite terminals have been listed. Multibeam phased array design strategies and challenges have been discussed with a focus on the front-end architectures. Hybrid beam forming utilizing multibeam subarrays has been encouraged. Several key research directions on front-end system design have been proposed.

Reflectarray Antennas for SATCOM User Terminals

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Introduction Reflectarrays provide a way for realizing low-cost, high-gain antennas and have been the subject of increasing research interest in recent years [24, 25]. The reflectarray combines some of the best features of the reflector antenna and the array antenna. It usually consists of a flat surface with many array elements and a feed antenna that illuminates the surface. The elements are designed to reflect the incident field such that a desired far-field can be achieved.

A large amount of the research on reflectarrays has been aimed toward space applications with a particular focus on satellite antennas. Reflectarrays provide attractive features in terms of manufacturing process and have been seen as an interesting alternative to reflector solutions. For these reasons, reflectarrays have been considered for contoured beam applications [26,27], high-throughput satellites (HTS) [28,29] and SAR applications [30]. An example can be seen in Figure 6 where the doubly curved reflectarray presented in [28] is shown. It is the first doubly curved reflectarray that has been manufactured.

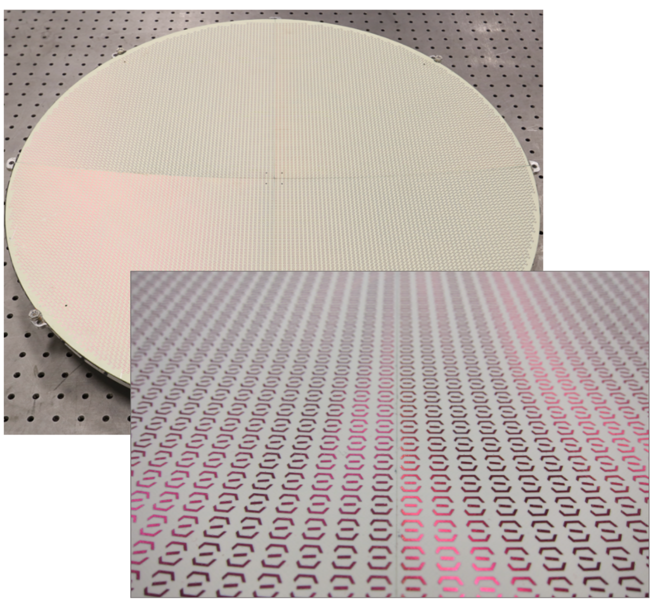

Figure 6: Doubly curved reflectarray for HTS [28].

One of the main challenges of reflectarrays for satellite applications is often related to thermo-mechanical issues, which degrade the RF performance of the reflectarrays. For these reasons, it is hard for reflectarrays to compete with conventional reflector solutions. Nonetheless, for mission specific applications, where reflectors can not be applied, reflectarrays can provide innovative solutions. This is for instance the case for the MarCO mission where folded-panel reflectarrays onboard CubeSats were deployed in space [31].

For terrestrial applications, where thermo-mechanical issues are less critical, there has also been interest in the use of reflectarrays for SATCOM user terminals as a compact and low-cost alternative to the conventional antenna solutions based on phased arrays or reflectors. Recent work mostly targets applications at K/Ka-band with operation at 20 (Rx) and 30 GHz (Tx) and circular polarization (CP). To this end, dual-band reflectarrays operating with a single aperture has been widely investigated [32–35]. Work for other bands are also of interest, Ku-band is still widely used also in new Low Earth Orbit (LEO) constellations, and potentially SATCOM will move into higher frequencies such as Q and V bands in the future. With the possibility of combining reflectarrays with other functional surfaces, e.g., frequency selective surfaces (FSS), additional operation bands could be added, providing additional functionality which otherwise can not be obtained using conventional reflector solutions [36].

Systems based on geostationary satellites require user terminals that can provide high gain and if used for on-the-move terminals also steering capabilities with a large motion range to cover high latitudes. Lower-orbit satellites also require user terminal with scanning and tracking capabilities, but may be able to operate with reduced scan ranges due to the amount of satellites and can also have lower requirements to gain. For the passive reflectarrays mentioned above, scanning and reconfigurability can be achieved by mechanical steering systems that are also used in existing reflector-based solutions. Using active reflectarrays [37], the mechanical steering can be avoided, and due to the flatness of the reflectarray, the antenna can be made more low profile compared to reflectors. This is highly sought after for mobile platforms on the ground, making the reflectarray a potential candidate for LEO user terminals.

The radiation pattern of the reflectarrays can be electronically shaped by making the array elements tunable by the introduction of varactor technology [38], ferroelectric films [39], PIN [40] and MEMS [41]. An example is shown in Figure 7 where a manufactured reconfigurable reflectarray based on varactors is shown. At higher frequencies, liquid crystals [42] have been investigated. Reconfigurable reflectarrays offer the advantages, compared to phased arrays, that they are cheaper and do not require beam-forming networks. However, one of the major limitations is that they have narrow bandwidth. Furthermore, the performance of active reflectarrays are inferior compared to their passive counterpart, and the realization of multi-band functionality is challenging.

Emerging challenges Going forward, for reflectarrays to be competitive compared to existing solutions for SATCOM user terminals, there are several challenges that need to be addressed.

For modern SATCOM user terminals, there is a request for the use of extended bands in K/Ka-band, i.e., 17.7-21.2 GHz in Rx and 27.5-31.0 GHz in Tx. Reflectarrays are narrow banded compared to reflectors. Covering the full bandwidth in both bands using a single aperture reflectarray is extremely challenging and requires advanced design. At the same time, the antenna needs to operate in dual-CP in both Tx and Rx. Most of the existing designs are dual-CP in the sense that they operates in

Figure 7: Reconfigurable reflectarray based on varactors in Ka-band [38].

RHCP in Rx and LHCP in Tx, or vice versa, but they need to work in both RHCP/LHCP in Rx and Tx. This combined with the extended bandwidth requirements is a challenge.

For on-the-move user terminals scanning capabilities are already mandatory, and with an increased interest in LEO constellations the demand for tracking and scanning capabilities will only increase. Making reflectarrays reconfigurable will significantly increase their potential, especially when considering LEO constellations with a lower requirement to scan range.

Future developments to satisfy these challenges Development of reconfigurable reflectarrays is a big driver to make reflectarrays competitive with conventional mechanically steered reflectors and phased arrays. Increasing efficiency and bandwidth of scanning reflectarrays is a challenging task that will require a lot of work on the technology used for reconfigurability and optimization of advanced array elements with a high bandwidth.

Another significant challenge with reflectarray antennas is that most of the research is carried out using general purpose solvers, e.g., HFSS, CST, etc. Although these general purpose tools can be used to design reflectarrays for demonstration purposes, the design approaches using these tools are too slow and have severe limitations in terms of realizing high-performance designs that can fulfill the requirements of real missions. For these reasons, most of the advanced reflectarray designs published in the literature are all done using in-house developed tools, where significant research efforts have been put into the in-house tools. It is not until recently that a dedicated design tool for reflectarrays, QUPES [43], was commercially released. Advanced designs tools are mandatory, if the reflectarray is to meet the stringent RF requirements for real practical solutions.

Conclusion Reflectarrays combine some of the best features of arrays and reflectors, both passive and active reconfigurable reflectarrays are interesting alternatives for modern SATCOM user terminals. This contribution briefly summaries some of the research on these topics and the shortcomings of the technology. Looking forward, there are interesting developments and investigations to be done such that reflectarrays can be a viable candidate for future SATCOM user terminals.

Programmable Transmitarray Antennas

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Introduction Transmitarray is very promising antenna solution for Satcom-on-the-move (SOTM) terminals. A transmitarray is a spatially-fed system based on a focal structure illuminating a flat or conformal textured surface. The use of multilayer printed circuit technology leads to cost-effective, robust, reliable, and ultra-competitive solutions for high-volume applications. Furthermore, thanks to their spatial feeding technique, transmitarrays, as reflectarrays as well, are extremely attractive compared to traditional phased arrays that suffer from large insertion loss of their (bulky) beam-forming network. Transmitarrays exhibit also a unique advantage compared to reflector antennas and reflectarrays: they can be integrated onto various platforms (buildings, vehicles, aircrafts, UAV, high-speed trains, public transportations, etc.) since they do not suffer from any feed blockage effect, thus leading to smart skins systems. Here, the term 'transmitarray' is chosen instead of 'meta-lens' because the periodicity is equal to half the wavelength.

In a transmitarray, the electromagnetic field distribution is controlled and manipulated locally thanks to several hundreds or thousands of sub-wavelength unit-cells disposed on a quasi-periodic lattice. Each unit-cell controls the transmission phase and/or polarization. As a consequence, by opportunely modulating the aperture phase distribution, it is possible to collimate, refract, or focus the electromagnetic waves in the near- and far-field region with specific properties in terms of beamwidth, side lobe levels, and polarization. Passive [44]- [53] and programmable [54]- [62] architectures have been successfully demonstrated in the literature.

Current state-of-the-art and advanced designs at Ka-band SOTM applications at Ku and K/Ka-bands require orthogonal or simultaneous polarizations between up-link (13.75-14.50 GHz, 27.5-31.0 GHz) and down-link (10.70-12.75 GHz,17.3-21.2 GHz) frequency ranges to improve the Tx/Rx isolation. Mechanical or electronic beam-scanning is required at the terminal to guarantee a reliable communication link with one or more moving satellites.

Two separate panels are typically used to facilitate the implementation of full-duplex SATCOM antenna systems. This leads to large antenna footprints that might be challenging to accommodate on moving platforms of limited size. In the last years, passive transmitarrays based on aperture-shared solutions with mechanical beam-scanning capabilities have been designed at Ku- [44]- [48] and K/Ka-bands [49]- [52] to reduce the overall antenna surface. They are based predominantly on interleaved unit-cells with a lattice periodicity larger than half a wavelength. Such a lattice size induces the appearance of grating lobes in the visible range while scanning the antenna beam over a wide field of view. Interleaved technology represents an excellent solution with an aperture efficiency beyond 50% [45] at Ku-band, where the ratio between the frequency bands is more favorable than at K/Ka-bands. On the other side, stacked architectures [50], [51] allow us to reduce significantly the lattice size, but at the cost of a more complex multilayer stack-up with an increased number of dielectric and metal layers. When the beam-scanning is implemented by displacing the feed across the focal plane, a limited field of view of around $\pm 30^\circ$ with scan loss > 5 dB is typically achieved. Moving the feed far away from the focal point produces increasingly spill-over and phase aberrations. To overcome these limitations, Risley prism [53] or bifocal [50], [53] architectures have been studied and demonstrated.

In theory, unit-cells with a fine phase resolution (i.e., a large number of phase states) are desirable to achieve high aperture efficiency and low side lobe levels. However, in the case of programmable transmitarrays, such unit-cells require several electronic components to control the phase states, which results in a number of limitations: higher insertion loss, variation of the insertion loss as a function of phase state, design complexity, and, at mm-waves, integration issues due to the small size of the unit-cell and the need to route DC bias lines. Moreover, when power consumption is a primary concern, a relaxed phase resolution can be chosen, at the cost of a higher quantization loss. Programmable or electronically-reconfigurable transmitarrays are typically implemented by integrating in the unit-cells electronic devices such as varactors [54]- [56], radiofrequency (RF) MEMS switches [57], and p-i-n diodes [58]- [61]. Even if solutions based on varactors enable a continuous phase range, they require a high number of devices and bias lines to cover the required 360° of phase shift. This hinders the realization of large arrays and degrades the bandwidth. On the other side, architectures relying on RF switches and p-i-n diodes are penalized by phase quantization loss, e.g. 3.5 dB for a 1-bit (i.e. two states with 180° of phase resolution). However, they minimize the number of devices and controls. Furthermore, wideband behavior can be naturally achieved by the particular phase-shift mechanism based on the control of the aperture current distributions [58]- [61]. Quantization loss does not correspond to an actual power loss but to a degradation of the focusing/collimating capabilities of the array, and leads to reduced directivity and aperture efficiency, as well as an increase of the side lobe levels.

One of the major challenge, in the field of programmable transmitarray for SOTM terminals, is the realization of both beam-steering and polarization electronic controls. To demonstrate this capability, sequential rotation schemes of randomly-distributed linearly-polarized unit-cells with 1-bit programmable phase control have been proposed in our pioneering work [60]. Random distribution has been used to mitigate the presence of quantization grating lobes when the beam is steered on the diagonal planes. 800 p-i-n diodes are integrated on a 400-unit-cell square aperture achieving a broadside gain of 20.8 dBic, a radiation efficiency of 58%, and a 3-dB bandwidth of 14.6% (27.4-31.7 GHz). The major limitation of this approach comes from the 3 dB of loss due to the fact that circular polarization is achieved by combining linearly-polarized unit-cells. This loss added to the quantization loss limits the aperture efficiency to 9.5%. 2-D electronic beam-steering capabilities of ±60° and circular polarization switching have been verified experimentally. For all vertical cut planes, the axial ratio in the main beam is below 3 dB.

In order to improve the aperture eficiency, a new structure based on a 2-bit (i.e. four states with 90° of phase resolution) programmable unit-cell has been proposed recently [61], [62]. To implement the electronic phase control, four p-i-n diodes have been integrated into the proposed unit-cell. Transmitarrays based on this unit-cell architecture for future SOTM ground terminals have been investigated in [62]. Two square transmitarrays operating respectively in down-link and up-link bands have been designed considering realistic specifications. Switchable circular polarization has been achieved by opportunely combining two V- and H-orthogonally polarized designs. Both polarization switching and electronically beam-steering functions can be implemented by controlling the four p-i-n diodes integrated on each unit-cell. In the case of the down-link antenna (38×38 unit-cells), a peak gain of 28.7 dBic is achieved at 20.5 GHz. Instead, a peak broadside gain of 31.8 dBic is achieved at 30.25 GHz by the up-link antenna (50×50 unit-cells). The possibility to steer the beam up to 60° has been analyzed in simulations. The achieved patterns have also been compard to the ETSI EN 301 358 radiation mask requirements.

To demonstrate the proposed design a quarter of the up-link panel has been fabricated [61]. It includes 2304 p-i-n diodes integrated on a 24×24 unit-cell square aperture (see Fig. 8). A 10-dBi pyramidal horn has been used as a focal source. The focal distance is equal to 7 cm. The antenna system has been characterized at the CEA-Leti anechoic chamber. The measured radiation patterns for a selection of 30.25-GHz-beams are presented in Fig. 9. As per simulations, the peak broadside gain is 25.5 dBic at 30.75 GHz, corresponding to an aperture efficiency of 18.0%. The peak gain is slightly shifted from the frequency were the phase distribution used to achieve the patters of Fig. 9 is optimized. Thanks to the improved phase resolution, this efficiency is about twice that attained by dual-circular polarized transmitarray presented in [60]. The aperture efficiency is still limited to the 3 dB of loss due to the sequential rotation. Furthermore, in agreement with the unit-cell radiation pattern, the scan loss is equal to 1 dB at 30° and 4.6 dB at 62°.

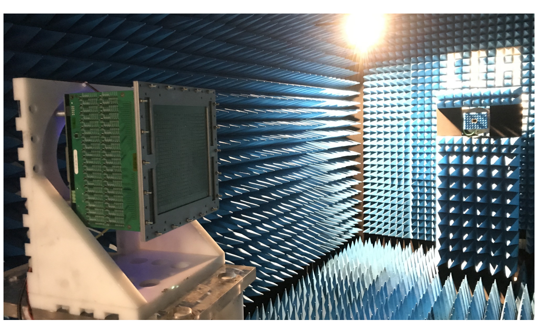

Figure 8: Photograph of the programmable transmitarray prototype operating at Ka-band mounted in the CEA-Leti anechoic chamber.

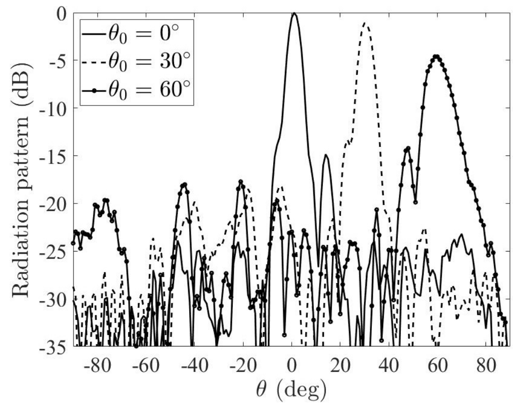

Figure 9: Measured radiation patterns of several RHCP beams on the E-plane.

Emerging challenges and future developments to satisfy these challenges Operational, regulation and cost constraints, for both civil or military SOTM applications, are extremely severe. Additional research efforts are required to developp a programmable transmitarray based antenna solution to meet the challanges of the next-generation SATCOM terminals.

Firstly, to circumvent unintentional interferences in transmission and reception, the power masks defining the levels of the side and diffuse lobes are extremely strict [62]. Thus, for a 30 dBi gain antenna, the level of the diffuse lobes must be 40 dB below the main lobe. Solutions to improve the programmable transmitarray phase resolution based on hybrid p-i-n diode/varactor unit-cells can be studied. Furthermore, the even more limited available surface and volume to install the antenna system on mobile ptaforms makes it essential to use ultra-low-profile aperture antennas with extremely high aperture efficiency. Near-field illumination with conformal focal systems enables a focal distance reduction of a factor between 2 and 4 [63]. Alternative solutions to achieve low-profile transmitarrays are based on the use of leaky-wave antennas as focal system [54]. The focal system definition should be selected opportunely to make an acceptable trade-off between bandwidth, scanning performances and side lobe levels. Programmable transmitarrays with shared Tx/Rx apertures can be developed based on the passive demonstrations [44]- [52]. Electronically-reconfigurable transmitarray combining high-phase-resolution unit-cells and programmable linaer-to-circular polarization converter represents an efficient solution to mitigate the 3 dB loss due to the circular poalrization control. Finally, integrated RF-switches based on CMOS processes or phase change materials, and high-efficiency GaN power amplifier technologies should be developped to extremely reduce the power consumpions of both the beam-forming system and the rdaiofrequency transceiver.

Acknowledgment

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Electronically reconfigurable metasurfaces

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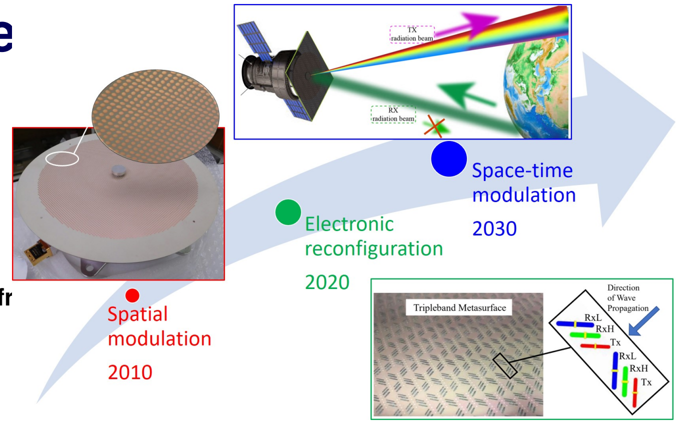

Figure 10: Evolution and future for electronically reconfigurable MTSs. Insets from [68, 71, 75]

Introduction In the last years, we have witnessed the deployment of 5G networks in metropolitan areas to cope with the global increase of mobile data traffic and the race for data rate. However, high-speed internet access is also demanded in remote or rural areas and in moving platforms, such as trains, aircraft and automobiles. In this context, satellite communications must enter into play to fill the gaps left by land-based services. Several initiatives, such as those of SpaceX, Telesat, OneWeb, and Amazon, are currently working to grant ubiquitous internet access [64].

One of the main challenges for accomplishing this objective resides in developing compact radio-frequency front-ends compatible with the form factor and aerodynamics of the moving platform. Metasurfaces (MTSs) are excellent candidates to reach that goal on account of their low-profile, low-weight, and accurate control of the aperture fields. Such characteristics are also attractive in case of natural disaster or conflict, because they enable a rapid and easy deployment. In holographic [65] or modulated MTS antennas [66], a reference wave (often a guided or slow wave) is transformed into the object wave (the desired radiation pattern) after interacting with an interference pattern or impedance modulation. As opposed to transmitarrays and reflectarrays, the source in these structures is embedded in the antenna aperture so they feature a zero focal distance. Holography has enabled the design of shaped beam, multiple-beam, dual-frequency and broadband antennas [67] with static (as opposed to reconfigurable) surfaces. Nonetheless, the latter approaches cannot provide continuous beam scanning, which is one of the key features to achieve seamless connectivity. The most immediate solution consists in introducing a mechanical rotation to get a conical sweep [68] (see Fig.10) or in adopting Risley MTS to obtain a two-dimensional scanning by two rotations, as in [69].

Despite providing an effective solution, the motors in mechanical steering are power hungry and a failure can render the system completely unusable. This aspect is particularly concerning in the space segment, where the repair or replacement of the RF front-end is not possible. The electronic reconfiguration of MTS elements constitutes a robust solution, since one can typically afford malfunction of tens or even hundreds of elements among a typical total of thousands. This is the reason why electronically reconfigurable MTSs have recently drawn a lot of attention. Such reconfiguration is achieved by resorting to liquid crystals [70, 71] or active elements, such as PIN [72, 73] or varactor diodes [74]. Fig.10 shows the reconfigurable element in [71]; this solution builds on LCD display technology and uses a liquid crystal optimized for the microwave range as tunable dielectric; a thin-film transistor matrix controls each MTS element individually.

Emerging challenges Terrestrial and satellite networks will have to provide data rates of hundreds of Gbps (and even Tbps) to cope with the growth of mobile data traffic. However, a more efficient use of the licensed spectrum will not suffice to reach the predicted data rates, so one will have to exploit the large bandwidths available in the sub-THz range (>100 GHz) [76]. As a result, electronically reconfigurable MTSs (typically implemented at Ka band or below) will have to operate at higher frequencies and be space qualified. On the one hand, it is challenging to find commercial active elements operating at such high frequencies in the space segment. On the other hand, the dimensions of the MTS elements may require even micrometer precision for an accurate fabrication. Such small dimensions will also demand innovative strategies to accommodate the biasing network.

Besides dealing with operation at higher frequencies, reconfigurable MTSs panels should also evolve towards curved or faceted surfaces to efficiently exploit the chassis of airborne platforms or reduce the aerodynamic loading. The design of conformal MTSs implies overcoming several hurdles such as finding appropriate materials and architectures for the integration of the electronics, as well as accounting for surface-wave and creeping-wave propagation and leaky-wave radiation [77].

Finally, all the aforementioned challenges should be addressed while guaranteeing a low power consumption and bearing in mind the transition towards a green electronics for a more environmentally friendly production and material choices.

Future developments to satisfy these challenges One will have to devise reconfigurable surfaces able to work in the *sub-THz regime* to cope with the first challenge in the previous paragraph. To that end, it will be crucial to exploit the ongoing advances in silicon-based (CMOS, SiGe:SiGeC or bipolarCMOS (BiCMOS)) and III–V devices (for example, InP HEMTs and HBTs) [78] to achieve reconfiguration at such high frequencies. One may also imagine using the same semiconductor substrate to host concurrently the active and radiating elements, as proposed for GaAs in [79]. Increasing the power handling capabilities of this devices will be also crucial to adopt the proposed solutions in the space segment.

Future developments can also find an opportunity in *optical materials and photonics*. For instance, photoconductive switches may be exploited to locally change the properties of the metasurface element [80]. Since such elements are activated by optical signals, the radiating elements and the biasing network can be decoupled simplifying the design.

On the other hand, new functionalities may be added to reconfigurable metasurfaces by introducing a change of states continuous with time. *Space-time modulated* MTSs have been recently studied to overcome some limitations of static and reciprocal MTSs. The use of space-time modulated MTSs may confer to the structures at hand: spatiotemporal decomposition, nonreciprocal transmission, serrodyne frequency translation, pure frequency conversion, and multifunctional operations [75].

The transition towards *green electronics* will introduce the need of using recyclable inorganic materials with a long lifespan and organic and/or biodegradable electronic materials. Among the most popular inorganic possibilities one finds aluminum, borosilicate glass, iron alloy, and graphene. Regarding organic materials, it is worth mentioning paper and wood-derived materials [81], resins, gums, saccharides, cellulose, gelatine and peptides.

Finally, in a global context where energy is a precious resource, the *energy efficiency* (bits/J/Hz) will become a fundamental key performance indicator (KPI) to assess the appropriateness of the different solutions.

Conclusion During the last decade, we have witnessed the dawn of electronically reconfigurable MTSs. This exciting field is in continuous development and it will have to face new challenges in the near future, including: the conquer of sub-Thz frequency bands, the efficient use of space-time modulations, and complying with the ecologic transition by adopting green materials and optimizing the energy consumption.

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Antenna integration technology

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Introduction One of the most common requirements of modern antenna systems is the high integration density that is the capability to implement exceptionally dense circuits where radiating elements, electronics, interconnects and DC/control lines are tightly distributed across multiple technology domains. Different technologies are used to combine multiple components and functions onto a single system, and to protect the circuit from external factors such as temperature and moisture. The possibility to have different implementation solutions for the building blocks of the same antenna system can be functional to a reduction of its cost, size and mass or to affect its final performance and functionalities. This aspect is particularly important for millimeter wave systems where the constantly increasing demand for reconfigurable systems makes integration aspects a key enabling technology.

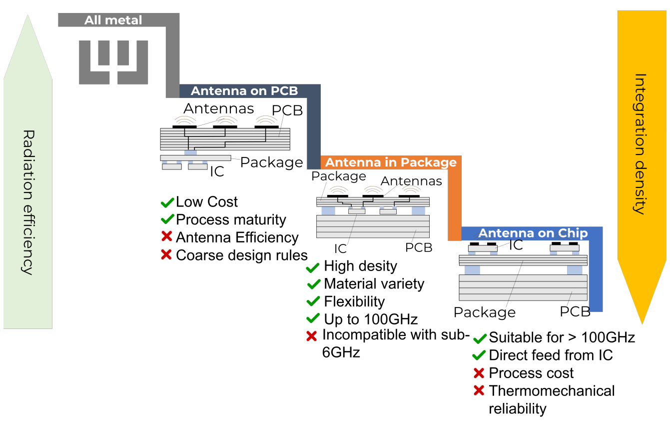

Figure 11: Antenna integration domains

Antenna architectures and integration domains The antenna architecture and the technology employed to integrate the radiating elements is fundamental to define the antenna system architecture. For fixed beam radiators or when a simple beamforming scheme is employed, antennas can be implemented using all-metal structures which allow the highest efficiency. These configurations require waveguide-to-printed circuit board (PCB) transitions [82] to enable an effective integration of the electronic circuits needed to implement, for instance, switched or multibeam architectures. When the frequency or the density of the front-ends increases, different integration solutions should be taken into account. Changing the integration domain reduces the antenna efficiency but it permits to increase circuit complexity as it is requested, for instance, in phased arrays where multiple vertical interconnections are needed within the same unit cell. For phased arrays or, more in general, for complex antenna architectures requiring an extensive use of monolithically integrated front-ends, the density of the interconnection is one of the key elements in defining the integration strategy. This aspect is particularly important for mm-wave phased arrays where each radiating cell, whose size is directly linked to the operation frequency and it usually does not exceed $\lambda_0/2$, can require multiple RF transitions to the monolithically integrated front-ends. Packaging and assembly technologies employed for phased arrays are usually inherited from digital electronic circuits where a wide range of solutions were developed [83] over the last decade. However, due to the need to preserve a high stability of the electromagnetic environment and to reduce losses, less complex architectures are typically taken into account. For this reason, Antenna in Module (AiM), Antenna in Package (AiP) or Antenna on Chip (AoC) configurations (11) are usually preferred for mm-wave applications [84, 85]. The location of the radiating element does not only determine the overall radiation efficiency but it also affects the overall integration approach affecting also thermal management and the final cost.

With the AiM solution, antennas and other passive components are assembled on a module typically realized in PCB technology thus allowing the implementation of arrays of large size [86] . However, in case of phased array architectures, each radiating element should be connected to an Integrated Circuits (IC) thus requiring several RF, DC and I/O interconnections. RF ICs can be integrated directly on the module or they can be embedded in a package. AiP approach is usually preferred when modularity and scalability [87] are required. With this approach, the RF ICs can be embedded in the same package or more complex integration schemes can be employed using, for instance, 2.5D or 3D assembly techniques. The monolithic integration of the radiating elements (AoC) is usually employed for low gain applications. Indeed, monolithically integrated antennas have inherently low gain performance due to the low resistivity of the silicon substrate and to its high dielectric permittivity which enforces most of the field to be confined within the substrate and not radiated in free air [88]. To overcome this issue, several solutions have been proposed in literature including the use of localized-backside etching (LBE) [89], the proton implantation process [90] or the use of parasitic elements [91]. On the other hand, AoC approach is highly attractive for specific mm-wave applications where the possibility to integrate the entire system on-chip is of primary importance [92].

The different integration technologies provide antenna engineers with a wide set of building blocks which can be employed to implement different antenna system architectures. The specific requirements, including the final production cost, dictate the implementation choices that are strongly related to the operating frequency, to the overall size of the radiating aperture and to the beamforming scheme. Beam-forming techniques can be classified into three categories: analog, digital and hybrid. Analog beamforming is still largely employed to realize active phased array systems with a relatively low hardware complexity and power consumption. In this scenario, beam scanning is performed with passive elements. Amplitude and phase are controlled as modulated signals in the transmission mode. In the receiving case, signals from each antenna are summed before the analog-to-digital (ADC) conversion. In the case of Digital beamforming, the beam steering functionalities are entirely performed into the digital back-end employing a simplified version of the RF front-end. In this case, amplitude/phase variations are controlled as demodulated signals at transmit and processed after the ADC in the receiver. This solution can provide full beam control with several simultaneous beams and multiple apertures. However, when a large number of antenna elements and/or large instantaneous channel bandwidth are needed, the implementation of the signal processing back-end becomes complex. Hybrid beam steering techniques can provide a trade-off between performance and system complexity. In this case, the whole array is partitioned into subarrays whose input and output signals are digitally processed while the signals at the element level are controlled in the analog domain.

Interconnections and RF integrated circuits The ability to monolithically integrate different blocks within the same chip and to efficiently connect the various RF ICs to the radiating elements is essential for any beamforming configuration at mm-wave frequencies. For this reason, the technological and architectural achievements that have been made in the last two decades in the development of monolitically integrated front-ends [93] have been of extreme importance. All beamforming ICs do require low noise (LNA) and power amplifiers (PA) for the receive and transmit chains, respectively. For analog beamforming, phase and amplitude tuning is also needed whereas hybrid and digital beamforming requires up- and down-conversion chains. For both configurations, multi-core chips are generally developed using SiGe (silicon-germanium) based BiCMOS (bipolar-CMOS) or CMOS technologies which offer an excellent compromise between the system performance and the ability to integrate both RF and digital controls on the same chip. However, in some applications, it might be effective to use different technologies, taking advantage of the unique strengths of each technology and combine them to achieve better overall performance. This approach is referred to as heterogeneous integration. For instance, it can be advantageus integrating GaN (gallium nitride) based devices, with SiGe BiCMOS technology on the same substrate resulting in improved performance and integration efficiency [94]. Another approach, useful for large arrays requiring high-demanding digital back-end, is to use different modules for the RF and digital chips. Interconnection between RFIC and the package (or module) can be realized by implementing bond wire transitions, flip chip interconnects or ball grid arrays (BGA) [95]. The RF interconnections bridging different technology domains are usually implemented using ground-signal-ground (GSG) pads for single ended signals. The routing traces in package are typically implemented using coplanar waveguides (CPW). To feed the radiating elements, quasi-coaxial vias through a ground plane opening can be used or, in alternative, contactless transitions have been recently demonstrated [96]

Emerging trends and future challenges The field of antenna integration technology is receiving increasing attention from scientists and industry worldwide, especially because of the continuous frequency up-shift in wireless systems. In light of the multidisciplinary nature of the topic, innovations are required in both technological and design directions. Technology innovation in materials for microwave electronic packaging is expected to bring a substantial improvement in both modules and packages. Besides the manufacturing processes based on Low Temperature Co-fired Ceramics (LTCC) and Liquid Crystal Polymer (LCP), new materials are being developed to improve the performance and reliability of microwave electronic devices [97]. The research effort tackles three primary aspects: i) the reduction of the dielectric losses; ii) the thermal properties of the material (thermal stability or thermal conductivity); iii) adaptability to complex stack-up scenarios and ease of manufacturing. Thermal management is crucial in microwave circuits, as high operating temperatures can lead to decreased performance and even device failure. This problem is exacerbated in millimetre wave or THz circuits because of the limited space available to dissipate heat. As such, the advancement of technology in thermally conductive and dielectric polymer composites (TDPC) is a key factor in the enhancement of integrated electronic devices. Recent trends to accomplish this goal primarily consist of infusing polymer composites and ceramic fillers with nanoparticles, such as TiO2, to further enhance their thermal properties [98] achieving the goal to have thermal conductivity higher than 3 W/mK [99]. Heterogeneous integration will become increasingly important in future antenna systems as the demand for smaller and more efficient devices continues to grow. One of the most promising technologies for achieving this is the use of 2.5D and 3D integration techniques [83]. 2.5D integration involves stacking multiple dies, or integrated circuits, on top of one another and connecting them through a silicon interposer. This allows for a more compact and efficient design, as well as improved thermal management and signal integrity. A specific example of 2.5D integration technique is the fan-out wafer-level packaging (FOWLP) also known as fan-out package-on-package (FOPOP) or fan-out wafer-level packaging (FOWLP) that allows to have more die on a single package. 3D integration, on the other hand, involves stacking multiple dies vertically and connecting them through through-silicon vias (TSVs). This allows for even greater levels of integration and improved performance, but can be more challenging to implement than 2.5D integration. Both 2.5D and 3D integration technologies enable the integration of more components on a single device, which can lead to a more compact and cost-effective design, improved performance and enhanced thermal management. However, it is important to note that these technologies also come with their own set of challenges, such as increased complexity and cost.

Conclusions Due to the continuous frequency up-shift in wireless systems and to the increased complexity of these systems, the field of antenna integration technology will play a crucial role in the next decade. In parallel to the innovations in materials and integration technologies new design paradigms are required to bring substantial improvements in both modules and packages, with the potential to lead to smaller and more efficient devices, but also come with challenges such as increased complexity and cost.

Continuous Transverse Stub Arrays for Satcom Applications

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Introduction Continuous transverse stub (CTS) antennas are linear arrays of long slots or open-ended stubs excited by parallel plate waveguide (PPW) structures. In their standard design, CTS arrays radiate a linearly polarized (LP) field. The radiation mechanism, main architectures and methods to scan the antenna beam were first described in [100], [101]. Since then, CTS arrays have emerged as low-profile antennas enabling wide-angle scanning, and have become a relevant solution for Satcom-on-the-move (SOTM) terminals [102]. Generally, the Transverse Electromagnetic (TEM) mode of the PPW structure is used to feed the radiating elements, either in series or in parallel. Series-fed arrays are electrically thin and characterized by a leaky-wave operation, which makes the pointing direction variable with frequency [100]. Parallel-fed CTS arrays achieve ultra-wideband operation at the cost of a complex corporate feed network [101], [103], [104]. The active impedances of their radiating elements are almost frequency-independent over several octaves, even for steering angles close to the horizon [105]. Both series- and parallel-fed CTS antennas have to be excited by a line source. Continuous line source generators, such as a pillbox beamformer (see Fig. 12) [103], [104], and discrete ones, e.g. arrays of waveguides [106], [107] have been successfully associated to CTS antennas.

Beam scanning is achieved by properly modifying the phase profile enforced by the line source over the array. Mechanical solutions are the most mature. By displacing a feed in the focal plane of a quasi-optical CTS beamformer [103], a continuous coverage of the field of view in a single plane is attained. However, the quasi-optical system limits the scan range in elevation of the array, e.g. to $\pm 45°$ in [103]. A class of series-fed CTS antennas, the variable inclination CTS (VICTS) arrays [108], [109], achieves two-dimensional (2-D) beam scanning. To this end, the array of slots is mechanically rotated with respect to the PPW feeding network. In this way, the TEM mode guided by the PPW structure impinges over the slots with a skew angle, determining the required phase gradient for beam steering. The high-end Satcom systems produced by *ThinKom Inc.* are based on VICTS antennas. Fixed-beam CTS arrays can be also used as feeds of rotating Risley prisms to attain 2-D beam scanning. In [110], a Risley prism is illuminated by two crossed series-fed CTS arrays, enabling dual polarization. A scan range of 40° in elevation and 360° in azimuth is reported.Though suited to 2-D scanning, mechanical approaches require several motors and may impact on the antenna weight, costs, reliability and beam-steering speed. Electronic discrete beam steering in elevation has been proposed and demonstrated

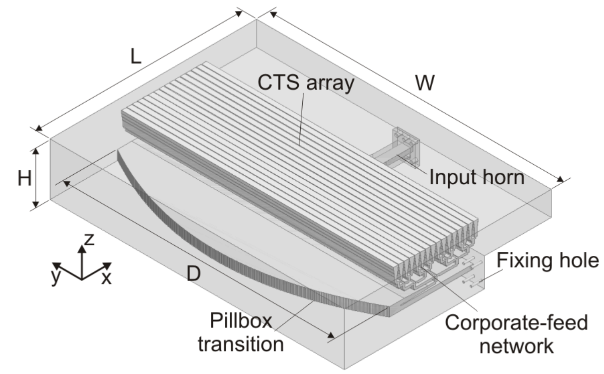


Figure 12: Perspective view of a CTS array fed in parallel by a corporate feed network and pillbox quasi-optical system.

in [111], by controlling 11 input feeds in the focal plane of a pillbox system exciting a parallel-fed CTS array. Each feed generates a beam pointing at a defined angle in the far field. Only one feed at a time is excited, by using a switching network. A field of view of $\pm 39°$ is covered. This electronic solution achieves fast beam-scanning and may pave the way for more robust, multi-beam Satcom links. However, the switching network introduces losses and possible power imbalance among the beams.

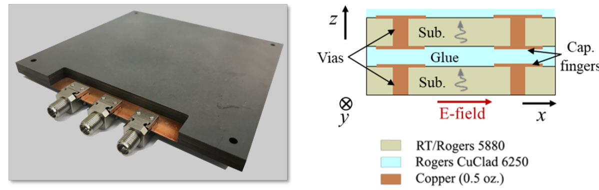
This brief state of the art has shown the potential of CTS arrays for SOTM terminals, which require ultra-wide fields of view to enable connections with constellations in various orbits. Next, the emerging challenges and future research directions are discussed.

Emerging challenges Modern Satcom terminals use two separate antennas for receiving (Rx) and transmitting (Tx) links, operating in orthogonal polarization and in two different frequency bands, e.g. in Ku and/or K/Ka-bands [102]. This solution ensures a high isolation between the links, but increases size, weight and costs of the terminal. The wideband operation of CTS arrays can enable the realization of a single antenna panel for both Satcom down- and up-links. This application need has been triggering an increasing research effort on novel solutions to design multi-band CTS antennas with polarization diversity. In [112], the radiating aperture of a VICTS antenna is shared by two independent feeding systems, operating in the bands 19.5-20.1 GHz and 28.8-29.6 GHz, respectively. A band-to-band isolation ≥ 20 dB is reported. The antenna height is only 10 mm, i.e. less than a free space wavelength at 29.2 GHz. However, it covers only small sub-bands of the allocated spectra for Satcom Rx (17.3-21.2 GHz) and Tx (27.5-31.0 GHz) links, mainly due to the series feed network. Moreover, the scan angles achieved in the two bands are not equal and their difference varies with frequency. The design in [113] mitigates this issue by using an aperture with two dedicated sub-arrays for the two bands, and also enhances the isolation (≥ 42 dB). For a given rotation angle of the array panel, the same pointing direction is attained in Rx and Tx bands, over a scan range of $\pm 47°$, enabling full-duplex operation. Furthermore, the use of slow-wave structures in the feed enhances the operating bandwidths

(19-21 GHz and 29-31 GHz). An aperture efficiency larger than 59% and 65.4% is observed at 20 GHz and 30 GHz, respectively. Shared-aperture designs covering two bands spaced far apart (e.g. in Ka- and W-band) and more than two bands have been recently reported [114], [115]. The fixed-beam parallel-fed CTS antenna in [115] works in the bands 11.25–15 GHz, 17.7–22 GHz, and 27.5–32 GHz, with gain higher than 24.7 dBi, 28.2 dBi and 32.1 dBi, respectively. The multi-band operation is enabled by an innovative six-port PPW multiplexer. An isolation $\geq$ 25 dB is reported.

The generation of circular polarization (CP) and the capability of radiating orthogonal polarization states (e.g. right-handed and left-handed CP) in the Satcom Rx and Tx bands are key challenges for the development of CTS-based terminals. The most common solution for CP generation consists in placing a polarization converter over a LP CTS antenna, as in [116]. However, this approach increases the antenna height and degrades both scanning performance and efficiency. Alternative CTS architectures use crossed radiating slots for achieving dual-linear [117] and dual-circular polarization [110]. This configuration is suited to series-fed CTS arrays, but does not ensure polarization purity and wide-angle scanning when the crossed slots are rotated with respect to the feeds. Thus, the use of Risley prisms [110] above dual-polarized CTS array was proposed to mechanically steer the beam, with drawbacks similar to those mentioned for a polarization converter. The novel concept of multi-mode polarization-agile CTS antennas has been advanced in [105], [118]. It is based on the excitation of a single array of slots by a bimodal PPW feeding network, supporting the TEM mode and the first Transverse Electric (TE) mode. The network has to prevent the propagation of the first Transverse Magnetic (TM) PPW mode, which has the same cut-off frequency of the first TE mode, to attain a proper dual-polarization operation. To this end, corrugated PPWs (CPPWs) were proposed in [118]. They do not support the first TM mode, but guide TEM and TE modes as in a standard PPW. A dual-LP parallel-fed CTS antenna with CPPWs has been demonstrated in [119], in the 29-32-GHz band. Its peak gain is 31.3 dBi. It covers a field of view of $\pm 22.5°$ using a pillbox beam former.

Another challenge is the development of technological solutions for the realization of CTS antennas, especially when fed in parallel, using affordable and robust fabrication processes. Indeed, corporate feed networks are conventionally realized with hollow PPWs, using costly milling and assembly of metal parts. Recently, innovative designs using additive manufacturing [119] or planar multi-layer processes, e.g. low-temperature co-fired ceramic [111] and printed circuit board (PCB) technology have been introduced. In particular, the wideband 8-element CTS array in [116] is realized in a single low-cost PCB. A picture of the prototype is shown in Fig. 13a). The array is fed by a corporate feed networks with vertical integrated PPWs, made with via fences. A standard design of this network requires blind or buried vias and yet may fail to ensure a good electrical contact among its stacked sections and prevent leakage. In [116], a low-loss contact-less transition between two stacked via-made PPW sections separated by a bonding film (see Fig. 13b) has been introduced. This solution enables the fabrication of a CTS antenna in a PCB with many substrates without using buried



(a) **(b)**

Figure 13: (a) Parallel-fed CTS array in PCB technology operating from 19 to 31 GHz [116]. (b) Section (xz-plane) of the contact-less transitions in the prototype. Vias along y-axis implement the metallic walls of the PPWs. Capacitive fingers around the vias guarantee the electrical contact amongst layers.

and blind vias, dramatically reducing costs and complexity. The antenna in [116] comprises 9 substrates and has an overall thickness of only 6 mm. It achieves the largest relative bandwidth ever reported for a CTS antenna in PCB technology, working between 19 GHz and 31 GHz, with a maximum gain variation of 3.2 dB. In addition, a pillbox system with 3 sources enables the radiation of 3 beams at 0° and $\pm 22.5°$ in elevation. The peak gain is 19.7 dBi and the radiation efficiency is 50%.

Future developments to satisfy these challenges The design of a CTS antenna covering two (or more) bands with a shared radiating aperture is yet to be addressed and will be a thriving research axis in the next years. Given the high band-to-band isolation between down- and up-link of a Satcom system, a filtering capability has to be integrated either over the array, in the feeding network, or in the active circuits driving the antenna. In all cases, higher complexity will be brought to these subsystems, as in [115]. Moreover, such filtering solutions should efficiently work over a large field of view.

New approaches to enable polarization agility will be key, using either innovative architectures, e.g. as in [119], or enhanced polarizing screens. They should ensure an operation over even larger field of views ($> 140°$) and bandwidths, with a limited impact on the system size, efficiency and scan loss. The capacity to radiate and fast reconfigure multiple beams will be an asset to guarantee robust Satcom links. Current mechanical-steering solutions should be then revisited to leave more space to an integrated electronic core. In this perspective, CTS arrays could be combined with programmable metasurfaces. New fabrication techniques will be a must to enable compact, flat and low-cost terminals. Additive manufacturing will be an attractive option, once the surface roughness is reduced enabling low losses. Besides, new methods to realize high-performance CTS antenna using planar multi-layer technologies could boost the mass-production of cost-effective terminal antennas, and the integration of CTS arrays in millimeter-wave systems.

Conclusion This paper has presented a brief overview on CTS arrays, with emphasis on possible Satcom applications. Starting from the state of the art, we have outlined current trends and future research directions to further improve this promising technology and provide low-profile, wide/multi-band polarization-agile antennas for SOTM terminals as a sustainable alternative to power-hungry and costly phased arrays.

Scanning antennas based on rotating/translating lenses for SATCOM user terminals

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Introduction The demand for high data rate mobile communications has continuously increased in the last years and a massive expansion of mobile satellite terminal market into new domains is expected in the future. The transportation industry, such as airline, bus and train companies, show a growing interest in offering fast and reliable data connections to provided passengers with high-speed internet access during their travels. The constant variations in the orientation of the moving vehicle with respect to the satellite requires user terminals with beam steering capabilities in order to lock the satellite signal and provide a steady communication. Such requirements make the antenna a critical component of the mobile terminal. Typical solutions to address the SATCOM mobility problem rely on either mechanically scanning reflector antennas, which suffer from bulkiness and limited scanning speed, or configurations bases on phased arrays, which offer fast beam steering at the price of high power consumption and complexity. In recent years, alternative solutions have been proposed, based on mechanically scanning mechanisms which can be a cost-effective compromise between the low profile typical of phase arrays, and the high efficiency possessed by the mechanical scanning parabolic dishes. These solutions permit the beam reconfiguration by either rotating or translating some flat lenses with respect to a primary radiator.

Rotating Metalenses One solution for high-performance mechanical scanning which does not increase the volume occupied by the antenna during the scan is based on the axial rotation of some antenna components. Risley prisms [120, 121] are a well-known example of such technique, although the bulkiness of the rotating dielectric wedges is not suitable for low-profile solutions required by the market nowadays. In recent years, planar versions of the Risley prism have been proposed [122]. A typical configuration based on rotating metalenses for beam scanning is shown in Fig. 14. The antenna is composed by a primary radiator topped by two rotating metalenses. Each metalens is free to rotate around its own axis independently from the other one and is also able to impose a phase gradient to the impinging wave which, in turns, is deflected after exiting the metalens by an angle that is related to the phase gradient. The independent rotation of the two discs allows to combine two different phase gradients in two different directions and this allows the antenna to achieve a full 3D beam steering. It is important to note that the two lenses can be stacked at a reduced distance (about one or two wavelengths) between them, and the same is true for the distance from the primary antenna; this feature produces a final antenna with a low profile. In principle, it is also possible to obtain the full beam scanning by using only one metalens, provided that the primary antenna radiates a tilted beam and is able to rotate around its own axis [123]; however, in practical implementations, this solution may suffer from lower system reliability and higher maintenance costs due to the presence of rotary joints or similar components.

The possibility to design flat versions of the Risley prisms introduced one of the main challenges that researchers are still facing, and the issue concerns the grating lobes that appear across the full radiation pattern, due to the periodic nature of these flat designs [124, 125].

Newer designs (such as the ones carried out by the team in Wave Up) are currently under development and implementation in order to strongly reduce the level of the grating lobes which, thanks to new design techniques, can be brought down to values of -25 or -30 dB over a wide band (see the measurements in Fig. 14). These latest developments could significantly improve the maturity of the flat rotating metalenses to be used in future low-profile, high-efficiency SoTM mobile terminals.

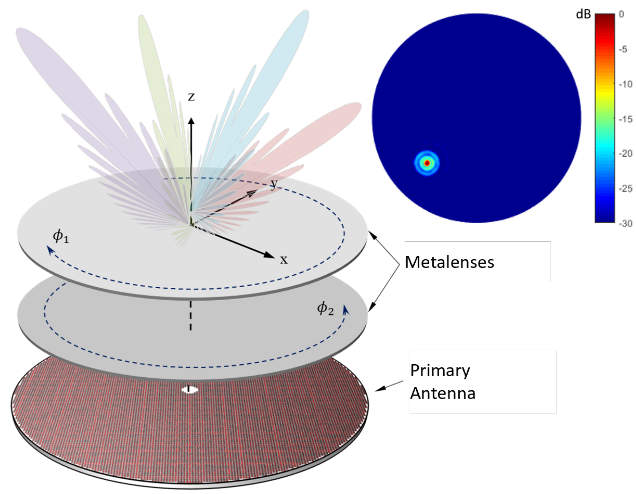

Figure 14: Beam-scanning antenna with two rotating metalenses.

Translating Metalenses An alternative in-plane mechanical beam scanning approach, that only requires one aperture, consist of two movements: i) a relative displacement between the primary source and the aperture for elevation scanning; ii) an axial rotation of the complete structure for 360-degree azimuth coverage (Fig. 15). The conversion of the lens (or feed) translation movement into elevation beam steering results from the use of the intrinsic aberrations associated to this displacement for producing the necessary linear phase shift. A more intricate balanced between maximum scanning range, aperture dimensions and focal distance of the antenna becomes necessary for managing these additional aberrations. The design challenge is combining low F/D and wide beam scanning with high performance. One of the concepts advanced by the team at Instituto de telecomunicacoes (IT), consists of an offset beam collimating lens illuminated by a primary source with a displaced phase center (virtual focus), that reduces the overall antenna height and preserves the same F/D performance of the aperture (Fig. 15) [126]. Other proposed solutions use generalized phase corrections (such as bifocal, [127] multifocal, etc.) or brute-force numerical optimizations [128] for providing a more even distribution of the intrinsic aberrations among all scanning beam directions, thus improving the overall scanning performance of the antenna. The optimization of the aperture considering multiple source positions can also be applicable for multibeam antenna design [129].

The primary source poses additional design challenges. Many of the SoTM specifications, such as dual band operation, dual orthogonal circular polarization operation needs to be implemented at the source level, without excessive complexity and cost. By co-designing the primary source with the aperture phase correction, new degrees of freedom can explored for further improving this mechanical scanning approach. Some proof of concept prototypes that support the aforementioned SoTM antenna specifications have also been developed by IT team [130]. There is still potential for further integration and optimization of all these components in more compact structures for improving the overall performance of this cost-effective solution.

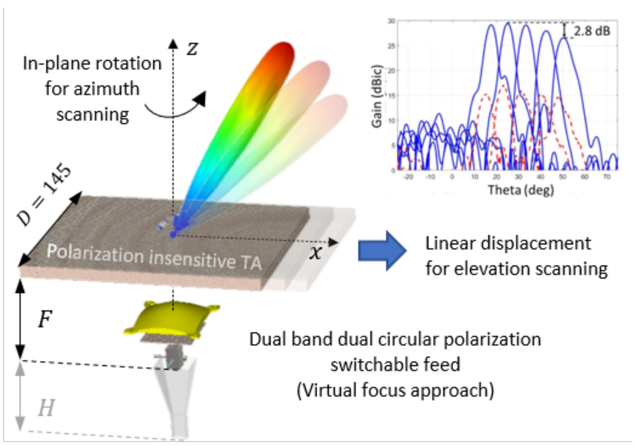

Figure 15: Beam-scanning antenna based on the translating lens and design challenges for SoTM applications.

Conclusion For many cost-driven applications with moderate beam agility requirements, mechanical beam steering can be a more suitable technology than electronic steering antennas. The ongoing massification of satellite broadband access is prone to increase the market for new mechanical based solutions that can still be compact and have good performance (as phased arrays) and low cost (in the same order than reflector antennas). In this work we have shown two complementary scanning solutions relying only on in-plane movements, which favors the integrability of this device and reduce the size of the antenna comparing with classical bulky reflector antennas counterpart.

Acknowledgment

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Quasi-Optical Beamformer for SATCOM Applications: Current Achievements and Future Research Directions

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Introduction Directive antennas capable of generating multiple beams are a key asset to next generation satellite systems for Satcom applications to establish agile and robust links. In this context, phased arrays offer high agility and reconfigurability with the drawback of complex, power-hungry and costly feed networks. Passive beamforming networks such as Blass or Butler matrices are another attractive alternative. However, the complexity and insertion loss of such networks increase rapidly with the number of generated beams limiting their use for space applications.

In recent years, quasi-optical beamformers (QOB) have received increasing attention in the field of space applications and beyond [131]. The major advantage of QQB is their true time delay nature, and thus large bandwidth and stable pointing direction. The following overview focuses on integrated QOBs based on different technologies and operating at millimeter-wave frequencies and in particular K/Ka-band to assess the technological opportunity for next generation Satcom systems. The capability of QOBs to illuminate direct radiating apertures and arrays of elements is discussed. 2D combinations of such beamformers can be also adopted to steer the main beam of an array or radiating aperture in free space.

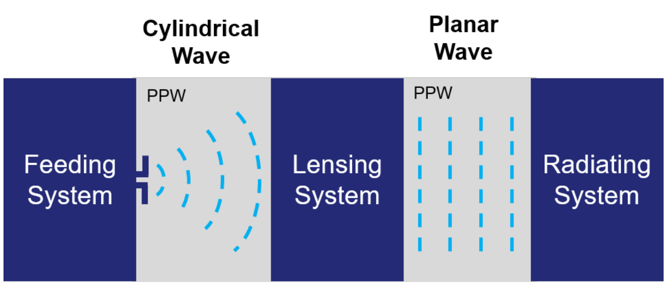

Figure 16: Schematic view of a planar quasi-optical beamformer in parallel-plate waveguide (PPW) technology.

QOBs are based on three building blocks/parts as illustrated in Fig.16: a source or feeding structure; a lens-based system; a radiating part or a sampling area. The operation of QOBs can be described as follows. A source or feeding structure integrated into a Parallel Plate Waveguide (PPW) environment launches the Transverse Electromagnetic Mode (TEM) of the PPW with a cylindrical wavefront. The lens-based system then shapes the wavefront of the TEM mode to provide, generally, a planar wavefront. The generated mode is then sampled/radiated either by an array of probes/radiating elements or another rack of vertical QOBs or directly radiated by an aperture at the edge of the QOB. Multiple sources can be also located in the focal plane of the QOB to generate multiple beams in free space (Fig.17 (a)). QOBs can be stacked as shown in Fig.17 (b) to provide very directive beams or the full coverage of the hemisphere as shown Fig.17 (c). Besides, hybrid beamforming configurations can be achieved by combining QOBs with circuit-based beamformers as shown in Fig.17 (d). In the following, key examples of QOBs

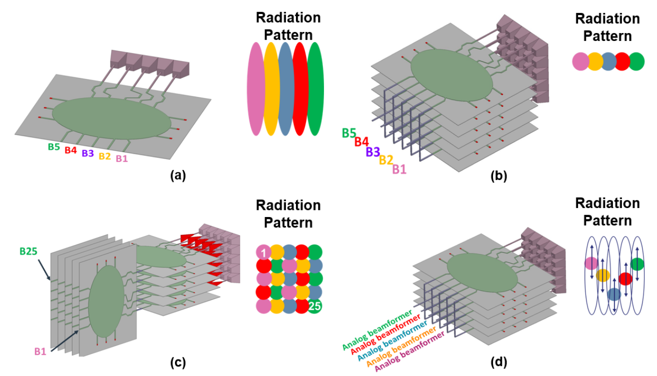

Figure 17: Schematic view of possible QOB configurations and sketch-view of the generated radiation patterns: (a) Single QOB with wide beams, (b) 1D QOB stacking with beamforming, (c) 2D QOB stacking with pencil beam radiation, (d) Hybrid beamforming.

from the literature will be reported and their advantages and limitations outlined. The various QOBs will be classified based on the number of foci supported by the system. Challenges and near-future research directions will be then outlined to further explore such technology for space-related applications.

QO-1: Pillbox beamformers The simplest example of QOB is the pillbox beamformers made by a parabolic reflector integrated into a PPW. The QOB provides a single focus and different phase gradients of the excited mode can be achieved by placing various sources along the focal plane of the parabolic reflector. Multi-layer implementations of the concept are generally preferred to avoid feed blockage with a more compact solution. Different implementations of the concept have been proposed during the years in various fabrication technologies (e.g. computer numerical control (CNC) milling [132], Substrate Integrated Waveguide (SIW) [133], etc.). The capability of the QOB to steer the main beam up $\pm 45^\circ$ has been demonstrated in [132] over the entire Ka-band.

QO-2: Rotman Lenses The Rotman lens is possibly the most well-known implementation of QOBs providing 3 foci and realized in a variety of technologies (e.g. CNC milling [134], Substrate Integrated Coaxial Line (SICL) [135], etc.). Rotman lenses are based on a PPW section forming the focal region of the QO system and a discrete guiding structure to opportunely sample and phase the TEM mode of the PPW before feeding a linear array. Such QOBs provide a large field of view over a wide band. As an example, an antenna generating 7 beams covering a field of view of $\pm 45^{\circ}$ in the band $25-45$ GHz has been reported in [135].

QO-3: Multi-foci QO systems The possibility of having multi-foci is extremely appealing to reduce phase aberrations and scan losses of the QOB. Lens designs based on continuously shaped PPW sections have been introduced [136]. In this case, the QOB shapes the wave front by either dielectric gradients or by transversely changing the profile of the lens within the PPW. An antenna providing 11 beams over $\pm 31.5^{\circ}$ in $27.5-31$ GHz band has been reported in [137].

Luneburg lenses in PPW technology provide the extreme case of having an infinite number of foci. They can be implemented by changing the refractive index of the media within the PPW. In addition, due to the azimuthal symmetry of the concept, the provided phase and amplitude profile of the generated TEM mode is independent of the feed location along the focal arc of the lens. Different implementations of the concept have been proposed in PPW technology (e.g. CNC milling [138], stacked PCB [139], etc.). An antenna operating in the $26-37$ GHz band and covering a field of view of $\pm 72^{\circ}$ with 11 independent beams has been validated in [139].

New implementations of geodesic lenses replace refractive-index-based solutions with non-planar PPW implementations in which the field propagation is engineered to achieve the required optical properties. Different implementations of the concept have been proposed in PPW technologies (e.g. CNC milling [140], etc.). An antenna with a field of view of $\pm 60^{\circ}$ covered by 17 independent beams has been reported in the band $26-35$ GHz in [140].

Emerging challenges QOBs present the main limitation of providing orthogonal beams while driving a single radiating aperture. A trade-off is then required to control at the same time the cross-over and side lobe levels (SLL) of the generated beams with the required efficiency. Such a challenge has been discussed in several works as in [141] and references therein. In [141] a split aperture decoupling method is adopted to cover a field of view of $\pm 40^{\circ}$ with 13 beams with a crossover level between adjacent beams of about -3 dB and a SLL lower than -24 dB for broadside radiation and better than -11 dB at the edges of the field view. An isolation better than 20 dB is achieved among the feeding ports. In [142] a two-feeds per beam excitation of a pillbox system is proposed to improve the cross-over level between adjacent beams. For this purpose, a passive circuit based on couplers and delay lines in SIW technology is proposed. 8 beams are generated with a cross-over level better than -3.2 dB in the band $76-86$ GHz.

QOB-based antennas generally radiate in linear polarization. However, dual and circular polarization are a common requirement, especially for Satcom applications. An emerging challenge is to propose innovative concepts to generate the required polarization agility. In [143], a back-to-back pillbox arrangement is adopted to feed two orthogonally polarized slotted waveguide arrays sharing the same radiating aperture. The antenna operates in the band $9.9-10.1$ GHz and provides dual polarization over a field of $\pm 36^{\circ}$ covered with 13 beams with a cross-over level of -3.3 dB. In [144], two QOBs illuminate a septum polarizer feeding a 1D array of square waveguides to generate 14 beams with alternating right/left handed circular polarization with an axial ratio below 3 dB over an angular range of $\pm 19^{\circ}$.

2D-QOBs as shown in Fig.17 require the connection of different racks of QOBs with a clear impact on the robustness of the concept, phase and amplitude variations and losses. Such challenges are particularly clear for QOBs feeding 2D arrays as in [145] where a double rack of Rotman lenses in PCB technology was used to feed a hexagonal array of 469 radiating elements to generate 61 beams. Similarly, in [146], a 2D hybrid beam forming is realized with a stack of four geodesic lenses fed by a feed network in rectangular waveguides. The whole setup is fabricated in aluminum by CNC milling. The system covers the $56-62$ GHz band with $\pm 55^{\circ}$ scanning in azimuth and $\pm 30^{\circ}$ in elevation. The measured gain is $1-2.5$ dB lower than estimated due to internal losses and mismatches showing the complexity of such kind of arrangements. Finally, such an arrangement, as also shown in Fig.17, will require extremely low-profile QOBs to avoid the appearance of grating lobes due to the physical size of the stacked QOBs.

Future developments to satisfy these challenges The challenges outlined in the previous section will require the development of novel concepts to provide QOBs operating over even larger fields of view and agile in polarization to serve wide band applications for space communications and beyond. Extremely compact solutions will be key to use QOBs for feeding planar arrays as in Fig.17 while reducing losses due to transitions or connections. Innovative solutions already aim in proposing multi-layer or folded QOBs. In [147], two ridges are introduced in an aluminum structure to reduce the profile of the lens while providing a large field of view of $\pm 55^{\circ}$ in the band $27-31$ GHz. Very recently, multi-layer reflecting geodesic lenses have been proposed [148], [149] paving the way for feeding planar arrays with wide fields of view and large bandwidths.

Multi-mode PPWs have been recently investigated to provide polarization agility to QOBs and related antennas as in [150]. Such a novel concept, while promising, should address the possible limitations in terms of band, phase distortion and feasibility. However, the possibility to extend the concept of QOBs to other guiding technologies may address such limitations.

Conclusion We have provided a brief overview on QOBs by outlining the current state of the art, emerging challenges and future research directions to further improve such a concept. QOBs provide an efficient and compact alternative to complex circuit-based networks feeding arrays or radiating apertures with a wide field of view and bandwidth for space applications or next generation communications networks.

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