Lenses Combined with Array Antennas for the Next Generation of Terrestrial and Satellite Communication Systems

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***Abstract*—The current worldwide energy and economical crisis triggers the need of more sustainable technological solutions to implement energy-efficient next generation communication systems, which should also be commercially viable and cost-effective. Moreover, future terrestrial and satellite communications will bring a wide range of use cases, services and environments with very different requirements and specifications to fulfill in order to generate a smart digital fully connected society. Designing new antennas for each single application is not feasible since it is very complex to meet the customer´s demand in the short run, and antenna system solutions that are easily re-configurable to be re-used in diverse scenarios are needed. The combination of lenses with traditional phased array antennas (also known as dome antennas) is a promising way of mixing the advantages of both antenna technologies and optimize the performance of our systems depending on the use case scenario. This article discusses the industrial and technical potential of using dome antennas implemented in different technologies for expected use cases and applications of future terrestrial and satellite communication systems.**

***Index Terms*—Array antennas, dielectric lenses, graded-index lenses, lens antennas, metasurfaces, millimeter-waves, radomes, satellite communications, terrestrial communications**

I. INTRODUCTION

THE raise of new use cases such as Internet of Senses, Machine Type communication, remote surgery and holographic communication, as well as the continuous exponential increase of mobile data traffic, involves the need of settling new spectrum allocation for the future scenarios and applications of the upcoming sixth generation (6G) of communication systems [1] which is expected to be deployed by 2030. It is envisioned that millimeter-wave (mm-wave) and sub-THz frequency bands will be highly relevant for 6G, and this brings technological challenges from the point of view of the hardware applied to implement the antenna system. On one side, integrated radio products operating beyond mm-waves require directive antennas to counter-back the high path loss at those frequencies. On the other side, in order to ensure the needed link budget and relax the power consumption from the power amplifiers, low-loss hardware technologies and low-loss materials need to be used. Moreover, robust and cost-effective manufacturing techniques must be employed in order to reduce the impact on the radio performance due to tolerances, as well as ensuring a viable commercialization of the system.

The right choice of the antenna solution employed in mm-wave and sub-THz systems is very critical, specially considering the fact that multibeam antennas with wide scanning capability must be used in order to provide enough coverage in the whole service area. Furthermore, electronic reconfigurability is an essential aspect of future radio systems in order to allow efficient connectivity on demand, and to be able to adapt the system to the use case requirements.

Phased array antennas (PAA) [2] have constituted a popular antenna option for radio products at mid-band frequencies (below 30 GHz) due to their beam steering capability, compact profile and design simplicity. However, as frequency increases, technology limitations and performance challenges arise such as high loss coming from the feeding network, integration challenges due to the high number of power amplifiers needed in order to achieve the required Effective Isotropic Radiated Power (EIRP) , and high cost due to the amount of needed phase shifters. Another inherent drawback of PAA is the reduction of the effective aperture area when steering towards extreme angles (usually beyond 60°), which results in high scanning loss. This increase in scanning loss is very critical since it limits the resulting coverage of the system, and it is mainly due to the flat profile of planar PAAs. Conformal PAAs could be an option to counter-back the scanning loss issue but they are complex to design and integrate into the whole radio system. Furthermore, many network vendors use sub-arrays in their base station products in order to increase the gain without increasing the number of radio chains, which results in the onset of grating lobes when steering the beam in the elevation plane. By not keeping those grating lobe levels under control, unwanted emissions above horizon might interfere with non-terrestrial systems like aircrafts, drones or satellites.

Using quasi-optical antennas such as Luneburg lenses [3]

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in next generation antenna systems, can solve some of the drawbacks of PAA. For example, two-dimensional (2-D) parallel-plate waveguide Luneburg lenses can be fully made of metal by either using metasurfaces [4] or geodesic surfaces [5], thus providing low loss. Moreover, the rotationally-symmetric nature of these lenses implies no scanning loss and inherent wide scanning capability in the lens plane without the need of phase shifters. However, achieving electronic beam switching and integrating fully metallic lenses into a traditional radio product involves drastic modifications in the system building practice which requires a big amount of design resources. Moreover, the applicability of lenses for terrestrial and satellite communications is mainly limited to frequencies beyond millimeter-waves. The reason for this is that, traditionally, lenses have been extremely bulky at low frequencies, so that other antenna technologies such as Massive MIMO become more interesting and feasible specially for sub-6GHz 5G applications.

In order to benefit from the advantages of both PAA and quasi-optical systems, one possibility is to combine both technologies generating the so-called dome antennas. Therefore, a dome antenna is a type of antenna that is enclosed within a dome-shaped protective cover. This configuration has been commonly used for wireless communication, such as in cellular networks, Wi-Fi, and satellite communication systems. The dome is typically used to shield the antenna from environmental factors like weather and physical damage. However, by providing lensing functionality to the radome (which is no longer transparent from the electromagnetic point of view) placed on top of a PAA, it is possible to improve or reconfigure certain aspects of the radiating performance of the PAA. This article describes the advantages, industrial opportunities and possible limitations of using lenses combined with PAA based on different technologies (metasurfaces, i.e. metadomes, and dielectric lenses) for emerging use case scenarios of future terrestrial and satellite communication systems. We expect this overview to provide an understanding of the industrial potential of using dome antennas and promote the investigation and development of innovative and cost-effective telecommunication products based on this technology.

II. DOME ANTENNAS FOR 6G MOBILE COMMUNICATIONS

The technology trend in the antenna hardware used in radio access base stations for future 6G systems is experiencing a drastic evolution mainly affected by several factors. A relevant one is the consideration of settling dedicating additional spectrum for 6G as, for example, the centimetric band (7-20 GHz), for use cases with mobility requirements and good coverage, and the sub-THz frequency range (90-300 GHz), for niche scenarios where extreme capacity and ultra low latency are required. This new spectrum needs to be allocated in order to allow the raise of a much wider variety of use cases, services and environments (see Fig. 1) compared to the ones envisioned in 5G. A consequence of having such an enormous range of applications with different types of requirements, is that the design, implementation, testing and development of a new antenna system product for each of them demand a lot of time and computational resources, as well as engineering efforts thus becoming neither commercially feasible nor cost-effective. Another critical aspect is the fact that the on-going energy and economic worldwide crisis requires the search of sustainable production processes, more energy-efficient integrated radio systems to reduce cost and power consumption, as well as seeking for re-configurability features of the radiating performance.

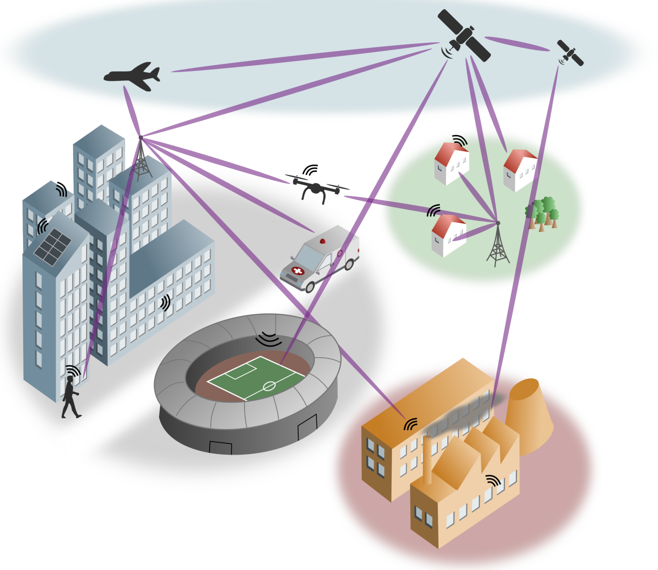
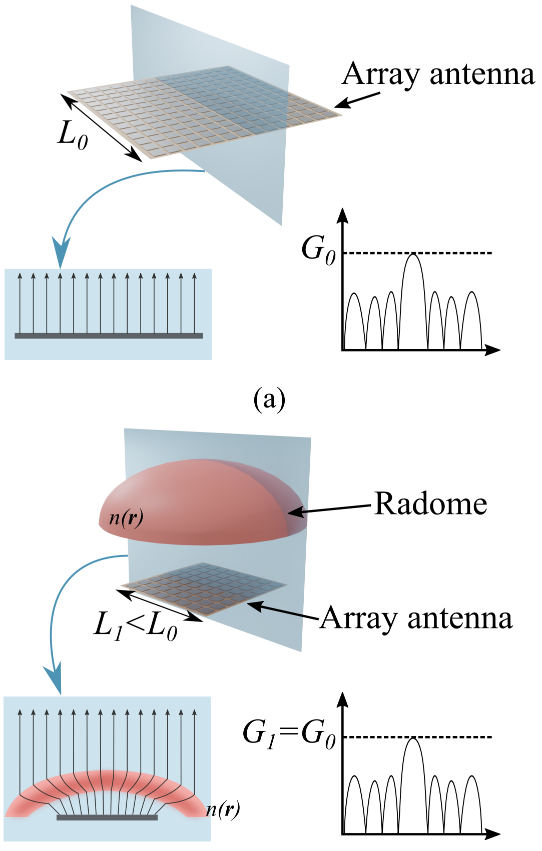


Fig. 1: Examples of 6G use cases and services.

Considering that reducing production cost and engineering efforts is a must for suitable industrialization of an antenna product, a very simple way to constitute flexible and innovative antenna systems is providing lens functionality to a critical component of the radio module that has been usually assumed just as a mechanical cover to protect the system from weather and other environmental conditions, i.e. the radome. By placing a lens on top of a traditional phased arrays, it is possible to enhance the radiation performance of the array or even re-configure its behavior to different use cases and scenarios. As an example, Fig. 2 shows one case where the use of a dielectric lens on top of the array permits to get a certain gain that would otherwise only be possible with a larger array with more elements. Moreover, it is possible to employ the same antenna array product for different applications by just applying a customized lens for each scenario. In this section, we present some key use case scenarios (see summary in Fig. 3) for 6G communications where combining lenses with arrays exhibit great industrial value, as well as a discussion of pros, cons and challenges of different technologies to implement the dome antennas for such scenarios.

A. Re-configurable operating scanning range

Re-using an available antenna array product for applications where different scanning performance is needed,



(a)

(b)

Fig. 2: Example of functionality of arrays combined with lenses. (a) Phased array antenna of size $L_0 \times L_0$ to achieve a targeted gain G_0. (b) Phased array antenna of size $L_1 \times L_1$ combined with a dielectric lens on top that achieves the same targeted gain G_0. The effect of the dielectric lens makes possible to use a phased array antenna with less number of elements, simplifying the feeding network.

can certainly decrease engineering and production costs. Fig. 3a depicts an outdoor street scenario where, to provide service to users along the street, the target performance from the dome antenna would be to achieve high gain and narrow coverage (close to broadside). On the other hand, Fig. 3b shows an indoor environment where a micro radio base station is installed in the ceiling of scenarios like airports, conference venues, offices... In such application, the wanted radiation performance is similar to a doughnut-shape coverage and the gain value at the broadside direction is not so important. Therefore, a certain degradation of the broadside gain could be allowed in order to enhance the gain at the extreme angles. The tailoring of the radiation performance of a single array for the use cases shown in Fig. 3a and Fig. 3b by customizing the geometrical shape of a dielectric lens has been theoretically proven in [6]. Moreover, the material properties of the dome were chosen to be able to act as a radome structure of the antenna system as well. One of the main challenges that were found during that proof of concept is the required simulation tool for designing and optimizing the lens shapes in an time-efficient way, in order to adapt the dome antennas to different scenarios. Full-wave simulations of dome antennas are computationally too heavy, thereby ray-tracing techniques (as similarly done in [7] for dome antenna design and optimization) are greatly needed keeping in mind that the lens geometry needs to constantly match the customer´s requirements. Apart of the use-case reconfigurability feature that was demonstrated in [6], considering sustainability and environmental aspects, it is of great interest for network vendors to develop more energy-efficient antenna products. In [8], it has been numerically proven that a dielectric lens may increase the gain of a PAA in a large scanning range (from 0° to 60° in the azimuth plane). The operating approach consists of providing a lens shape that increases the projected effective aperture of the array antenna at all scanning angles. The dome antenna was designed to operate in the 3GPP n257 band (26.5-29.5

Fig. 3: Examples of applications of dome antennas for 6G Communications.

GHz). At 28 GHz, the resulting gain increase when applying a lens on top of a PAA is 1.3 dBi at broadside and 0.4 dBi at 60°. This has an energy sustainable consequence since the output power of the power amplifiers may be decreased from 9% (at 60° scan angle) to 26% (at broadside), showing the capability of dome antennas to develop energy-efficient antenna systems.

Another relevant work on dielectric dome antennas which served as starting design point to the use case reconfigurability proof of concept of [6], is the one reported in [9]. Here, it was demonstrated that by using a dielectric dome antenna with low profile, the field of view of an array may be extended to angles up to 70° over 15% bandwidth. The demonstrator was built at K_u-band, showing an average gain increase of around 2 dB when steering the beam to 70°, with a gain degradation of 1.5 dB at the broadside direction. The size requirements of the employed lens limit the resulting gain performance, but if there are no constraints in the lens size the scanning loss can be decreased and better broadside gain may be obtained. In both research works shown in [6] and [9], matching layers are added to the dielectric lens to mitigate reflections. This is quite critical considering that reflections towards the phased array elements would have an impact in the active match and mutual coupling of the array. Furthermore, it is important to remark that in order to reduce the resulting scanning loss of a traditional planar phased array when scanning the beam towards extreme angles, the lens allocated on top of the array may not have a flat profile. By placing a shaped concave lens on top of a flat array, we can then increase the projected effective aperture from the array when scanning towards large angles, thus increasing the gain in those directions. This is actually demonstrated in the reported investigations of [6] and [9]. In [6], it is also shown that for increasing the gain at scanning angles close to broadside the dielectric lens should have a convex shape.

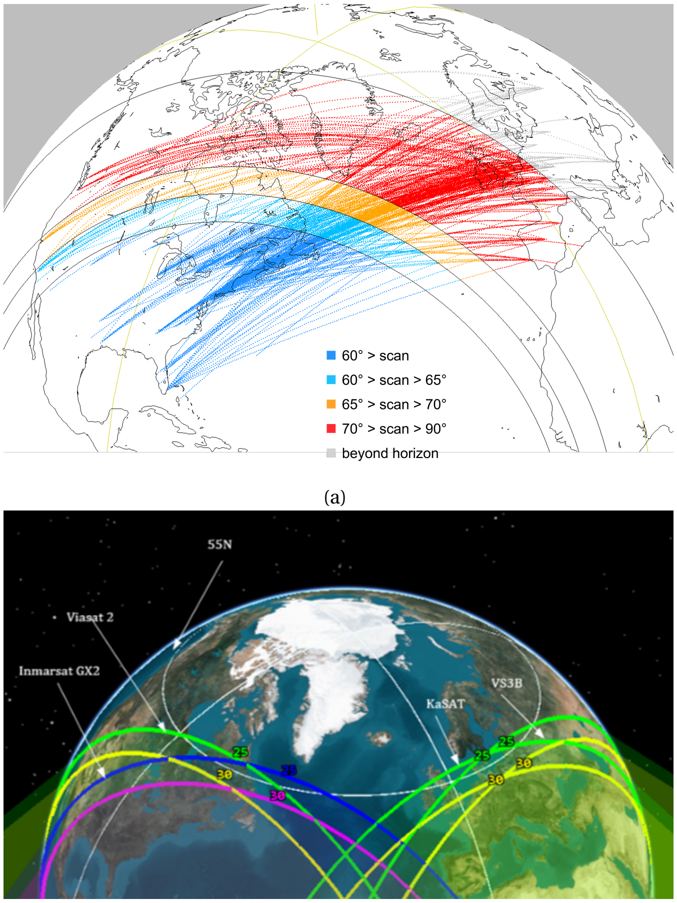
Considering a different technology to implement dome antennas rather than using dielectric lenses for enhancing the steering capability of an array, in [10] a two-lens system combined with a phased array based on Huygen´s metasurface unit cells (a wire-loop topology) is presented. This metadome (i.e. a metasurface based dome) system can provide a beam steering behavior from -30° to +30°, thus doubling the beam scanning performance from the source array which is only able to steer the beam electronically between -15° and +15°, without the onset of grating lobes. This approach requires the use of a converging lens and a diverging lens placed in the near-field region of the array. By doing this, it is possible to provide uniform phase and magnitude distribution to the array antenna, and obtain directive steerable beams at the output of the outermost lens. The output beam angle is then controlled by changing the focal length of the second lens and the distance separating both metalenses. Although the doubling of the operating steering angle of the array was here experimentally demonstrated, the application of metadomes based on Huygen´s metasurface unit cells has some practical limitations for the application on 6G radio base stations. First, the narrowband nature of this type of metasurfaces challenges the bandwidth requirements of 6G use cases. Second, metadomes cannot act as a mechanical cover to protect the radio system. Therefore, an additional radome would be needed to be placed on top of the two-lens system, thereby the profile of the complete dome antenna becomes too bulky for integration into a product.

B. Unwanted emissions suppression above horizon

One of the most relevant challenges of 5G and beyond mobile communication systems is to ensure service to a wide region and co-existing without interfering with non-terrestrial systems, thus avoiding unwanted emissions above horizon towards for example aircrafts, drones or satellites (see Fig. 3c). Using large sub-arrays in elevation to ensure the required EIRP for mobile broadband has constituted a common practice to implement 5G antenna systems. However, using sub-arrays with large inter-element distance triggers the appearance of grating lobes which point above horizon interfering with geostationary satellites or other airbone systems. Regulators like the 3rd Generation Partnership Project (3GPP) are currently working on settling levels of unwanted emissions that need to be considered in the design of next generation radio products in order to assure the co-existence of any type of communication system.

Different concepts of dome antennas have been recently introduced with the goal of reducing the level of grating lobes, thus decreasing such spurious emissions. One approach consists of using a plastic lens array combined with sparse 4 x 4 leaky-wave feeds (inter-element separation is 2 λ) as reported in [11]. Here, the mechanism to suppress the grating lobes while achieving high gain, consists of electronically phase shifting the array factor towards a desired angle as well as introducing a mechanical displacement of the lenses so that the lens element pattern combined with the array factor results in a low grating lobe level while steering. This concept has remarkable advantages, like providing wideband performance (over 20 %), high broadside gain at the center frequency, decent polarization isolation and an aperture efficiency of around 70 %. However, this solution comes with certain limitations that challenge its industrialization. One of them is that the optimum reduction of the grating lobe level requires mechanically moving the plastic lenses with respect to the sparse array, which adds complexity to the system. Another question mark is the application of this solution when wider steering capability is needed, since this proof of concept shows only ±10° operating scanning range in two planes with 2 dB of scanning loss.

In [12] a metadome implemented with ideal refracting Huygen´s metasurface unit cells is evaluated numerically, where the grating lobe level reduction is achieved by the so-called scanning range shifting approach. This method consists of shifting the scanning range from the array in order to avoid the grating lobes, and thereafter re-adjusting the propagation towards desired angles when applying the metadome on top of the array. In this investigation, a 10 dB grating lobe level reduction in the satellite angular region is obtained, while having a main beam gain degradation of around 1.42 dB. Therefore, a trade-off between insertion loss at broadside and grating love level reduction is neeed. This metadome concept has the advantage that can be applied on top of already existing antenna products, so that co-design of the metadome with the specific antenna is not needed simplifying the design process. Despite the resulting compactness of the metadome, an additional radome would be required to protect the whole system from environmental conditions thus increasing the profile of the radio system. Furthermore, the Huygen´s metasurface applied to implement the metadome is narrowband and can just provide around the same operating bandwidth as the PAA. Using a narrowband metadome at mm-wave frequencies can become a practical issue due to manufacturing and assembly tolerances.



(a)

(b)

Fig. 4: (a) Examples of coverage depending on antenna scan, considering only one satellite. In the same graph international flights for several airlines have been overlaid. (b) Examples of coverage for given phased array scan angle capabilities.

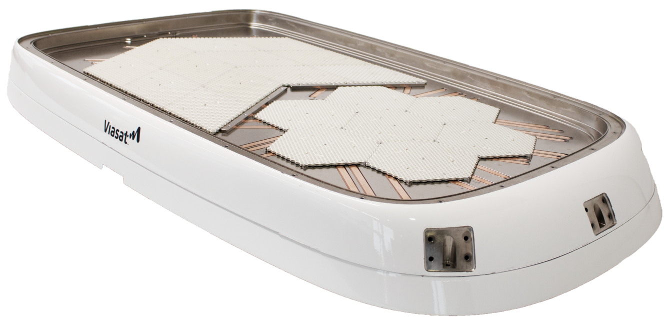


Fig. 5: Terminal designed for regional jets relying on phased array technology in K_a-band. The terminal was proven over the air during land and flight demos [13].

III. DOME ANTENNAS FOR FUTURE SATELLITE COMMUNICATIONS

Combining phased arrays and lenses may also yield interesting results for satellite communications. As mentioned before, phased array antennas are characterized by a decrease in performances as the scan angle increases. Most of the satellite product examples available on the market are showing a sharp drop in G/T (Gain to noise Temperature) and EIRP for scan angles above 70° [13].

This does not constitute a problem when the terminal is fixed or moves in a regional area as the United States or South Europe. Unfortunately, when the terminal is aimed to address high-latitude countries, or it is meant to be used for airborne application where connection is required over the ocean, PAAs connected to a GEO (Geostationary) satellite are not anymore an adequate solution. As an example, in Fig. 4a many of the flight routes connecting the United States to European destinations are shown with colors changing depending on the scan angle when only one GEO satellite connection is assumed. The red curves depict all flight parts that would require the antenna to scan larger than 70°. When adding other GEO satellites (Fig. 4b) the situation improves but a large gap in the coverage is still present.

Re-using the same array technology developed for regional jets and land mobile application (see Fig. 5) but being able to increase the coverage by reducing the drastic loss of performances with scan angle, is certainly of great interest. Resorting to dielectric domes with adequate matching layers should be regarded to as an attractive solution if the size and weight are appropriate. These indeed could be the main limitation for the adoption of such combined PAA and lenses technology. A careful design and choice of manufacturing materials is needed to avoid resulting into a cumbersome and ineffective solution.

An additional remarkable use case of applying dome antennas for satcom (satellite communication) applications is the reduction of power consumption and complexity of the array circuitry beneath. This is specially attractive for frequencies beyond millimeter-waves where a reduced inter-element distance would make the array routing and the placement of the array components prohibitive. By applying a lens that reduces the grating lobe level, we can allow for larger array element spacing and still keep decent scanning operability. This has sustainability consequences since using less antenna elements for a same antenna aperture implies: a) obtaining the same gain, b) reducing the number of RF chains, thus using less power amplifiers (PA) so that the power consumption of the whole system might be reduced (depending on the EIRP requirements), c) more room for active electronics integration and thermal cooling.

In [14], an X-band double layer metasurface-based lens placed on top of a phased array for satcom is reported. The metalens array antenna consists of 3 dual-polarized metalens elements, each fed by a circularly polarized patch antenna. The main objective of this work was to simplify the array architecture and reduce the number of phase shifters, thus decreasing the required RF chains in the system and consequently the cost. This specific solution is not based on attenuating the grating lobe level to allow for large inter-element distance. Therefore, the resulting scanning range is limited by the onset of grating lobes in the visible region. In this approach, only one phase shifter is needed for each lens element (3 phase shifters in total for the complete metalens array). Switched beams are then obtained when exciting different feedings in a single lens element, whereas steered beams are generated when varying the phase shift among the lens elements. The metalens phased array achieves ±30°coverage range with a scanning resolution of 6°. The final design is quite compact since the focal length is reduced to one-sixth of the aperture size. However, as mentioned before, metasurface lenses may not act as mechanical cover of the whole system. Therefore, an additional radome layer is required for protection.

IV. FUTURE RESEARCH LINES ON DOME ANTENNAS

Considering future research lines on potential applications and use cases of dome antennas for terrestrial communications, one interesting concept could be to employ this technology as a tool to improve the beamforming properties (like gain or coverage) of millimeter-wave Massive MIMO systems, as well as simplifying the implementation of such systems. This use case is inspired on the application of lenses onto Massive MIMO systems described in [15], where the usage of lenses combined with arrays is compared to fully digital beamforming (typical in Massive MIMO systems) and hybrid precoding. We envision that by combining lenses with arrays we can reduce the number of antenna elements for a same antenna array aperture (increasing the inter-element distance), thus achieving the same gain. This would result in a reduction on the number of RF chains, which may lead to a more cost-effective solution with lower power consumption (more energy-efficient systems). However, an accurate control of the grating lobe level is critical to allow for large inter-element distance. In fact, as mentioned in Subsection II.B, controlling the grating lobe level is also essential to suppress unwanted emissions towards non-terrestrial communication systems, being currently a high priority for 3GPP to set standards on those emission levels. Therefore, the investigation of dome antennas based on homogeneous dielectric materials (capable to act as radome) to reduce the grating lobe level without degrading the main beam performance, is one of the most relevant future research lines for next generation terrestrial communication systems.

Regarding the next steps on satcom systems, further innovation on dome antennas could be related to the application of new low loss dielectric materials, or methods to achieve the needed dielectric constant using lightweight airborne approved materials (for example by using innovative graded index lenses combined with arrays).

A common and extremely critical research aspect for both future terrestrial and satcom systems is the development of highly-efficient simulation tools based on geometrical optics (ray-tracing techniques) that are able to optimize in a time-efficient way the corresponding lens shape depending on the use case scenario. These ray-tracing algorithms should accurately evaluate the radiation characteristics of single and multilayer (for the case of non-homogeneous or graded-index lenses) dielectric dome antennas even taking into account reflection and absorption losses.

V. CONCLUSION

In this article, we have discussed the advantages, industrial opportunities and potential challenges of combining lenses with phased arrays to build up innovative and cost-effective antenna system products for different use cases of next generation terrestrial and satellite communication systems. This technology overview has focused on possible scenarios where dome antennas could improve the performance of traditional phased arrays, and a comparison between several recently reported lens solutions based on dielectric materials and metasurfaces has been provided. Table 1 summarizes the properties of the analyzed dome antenna technologies, although other concepts like graded-index lenses and additional types of metadomes not based on narrowband Huygen´s metasurface unit cells, could be innovative lines of research to develop next generation antenna products expected to fulfill the strict requirements of the envisioned applications of the future digital and fully-connected society.

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TABLE I: Summary of dome antenna properties based on dielectric materials or metasurfaces

Reference	Use case	Bandwidth	Technology	Radome capability	Compactness	Manufacturing	Operating approach
[6]	Use case reconfigurability	Wideband	Dielectric material with matching layers	Yes	Compact	Additive manufacturing	Change of effective aperture
[7]	Scanning range enhancement	Wideband	Dielectric material without matching layers	Yes	Bulky	Additive manufacturing	Change of effective aperture
[8]	Energy-efficient systems	Wideband	Dielectric material with matching layers	Yes	Compact	Additive manufacturing	Change of effective aperture
[9]	Scanning range enhancement	Wideband	Dielectric material with matching layers	Yes	Compact	Additive manufacturing	Change of effective aperture
[10]	Unwanted emission suppression above horizon	Narrowband	Huygen´s metasurfaces	No	Compact but needs a radome on top	Printed technology	Change of focal length of second lens and distance between lenses
[11]	Grating lobe level reduction	Wideband	Plastic lenses	Yes	Compact	Additive manufacturing	Combination of lens element pattern with array factor
[12]	Doubling scanning range without grating lobes	Narrowband	Huygen´s metasurfaces	No	Bulky	Printed technology	Scanning range shifting approach
[14]	Reduction of RF chains	Narrowband	Combination of multilayered patch cells with substrate through-holes	No	Compact but needs a radome on top	Printed technology	Phase shift profile variation discretized pixels

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