State-of-the-art Millimeter-Wave Beam-Steering Antennas for Beyond 5G and 6G Networks - A Comprehensive Survey

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Abstract

This is a review article discussing the latest developments in beam-steering antennas at millimeter-wave frequencies for Beyond-5G and 6G networks. This article classifies all the beam-steering techniques described in the literature in four categories, namely, phased arrays, quasi-optical systems, leaky-wave antennas, and metasurfaces. An overview of the four classifications is presented with a detailed comparison outlining the state-of-the-art and limitations of different technologies.

Introduction

Modern day wireless communication has started to become one of the basic necessities. It has led to a number of new technologies governing our day-to-day life such as the internet of things, connected and autonomous vehicles, telemedicine, deep space research, etc. With the introduction of such new technologies, the number of devices connecting to the public wireless network is multiplying rapidly and is creating a demand for high bandwidth and high data rates [1], [2]. With the rising user count, the present-day sub − 3 GHz public wireless network has reached its limit with not enough bandwidth for further developments and hence, a lot of interest is shown in using sub-millimeter and millimeter-wave bands (3 – 300 GHz).

The unused mmWave spectrum can offer a solution to bandwidth scarcity and cater to the growing number of users [3], [4]. The mmWave band, however, offers a short wavelength (1 to 100 mm), which undergoes several issues that includes atmospheric losses [5], rain attenuation [6], high path loss [7], low diffraction [8], [9], multipath delay [10], [11], and foliage loss [12]. As an example, a study concluded that mmWave bands can present an attenuation as high as 6 dB/km for a heavy rainfall of 25 mm/hr at 30 GHz, significantly impacting the tropical regions across the planet [13].

Beamforming is a method to focus the radiated power from a source in one direction, creating a highly directional beam [14], [15]. This highly directional beam can overcome the challenges of path loss, fading, and multi-path delay. Several field studies have demonstrated that beamforming-enabled base stations covering a radius of up to 200 m (and hence, creating pico-cells) are the way forward for enabling the upcoming Beyond-5G and 6G networks [16]–[18]. A reconfigurable antenna system can be designed to control and steer the direction of such focused beams. Such antennas are known as beam-steering antennas.

Beam-steering antennas have become a highly attractive area of research within the field of antennas and propagation for applications in not just 5G/6G networks but also in aerospace, satellite communications and defense. The keyword “antenna”, “beam” and “steering” was first used in 1935 [19] where steering of the antenna was used to reduce signal fading. Since then, the subject of beam-steering has grown over the decades. Figure 1 shows the rise in number of articles published on IEEE Xplore alone over the last ten decades (till March 2024). A notable growth is seen within the subject in the last decade with more than half the papers published in the last three years only.

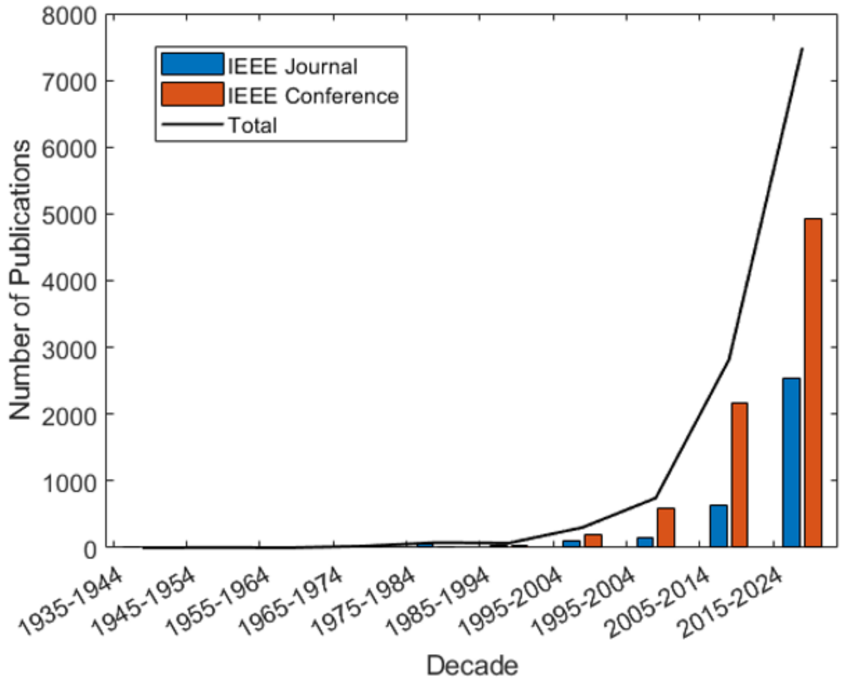

Figure 1: Number of papers published on IEEE Xplore with keywords “antenna” AND “beam” AND “steering” (Data till March 2024).

Several electronic beam-steering antennas are described in the literature using different innovative techniques such as phase-shifting, multi-feed, frequency selective surfaces, and metasurfaces. Different review studies have been conducted by different groups focusing on a single category such as reconfigurable leaky-wave antennas, phased arrays, and metasurfaces for beam-steering.

For ease of understanding and to establish a better comparison between different technologies, in this article, we have classified all the electronic beam-steering antenna techniques into four main categories, namely, (i) phased array antennas, (ii) quasi-optical systems, (iii) leaky-wave antennas, and (iv) metasurfaces, see Figure 2. This article gives an overview of the working principle of technology followed by state-of-the-art examples from the literature. Finally, we compare the capabilities and limitations of four different technologies based on real-life applications within beyond-5G networks.

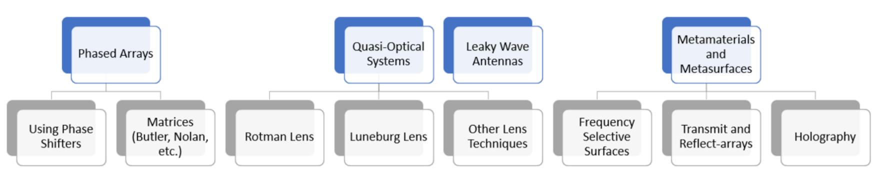

Figure 2: Four classifications and sub-classes of active beam-steering antennas.

Phased Array Antennas

Phased array antennas are one of the easiest ways to achieve beamforming and beam-steering. A phased array antenna can be understood using the analogy of an N -slit diffraction experiment where the overall beam from the array is a result of coherent constructive interference of$N$ sources (or independent antenna elements in an array). Each antenna element in the array is fed with a phase shift, introducing a time delay in the radiated beam. The constructive interference of these time-delayed beams from each radiating element enables directional control. A simple representation of the beam tilt because of the phase shift in different elements using an array of six open-ended waveguides is shown in Figure 3. The radiation pattern and tilt angle for such antennas can be estimated using the array factor. Detailed mathematics for the calculation of tilt angle is provided within the Supplementary Information.

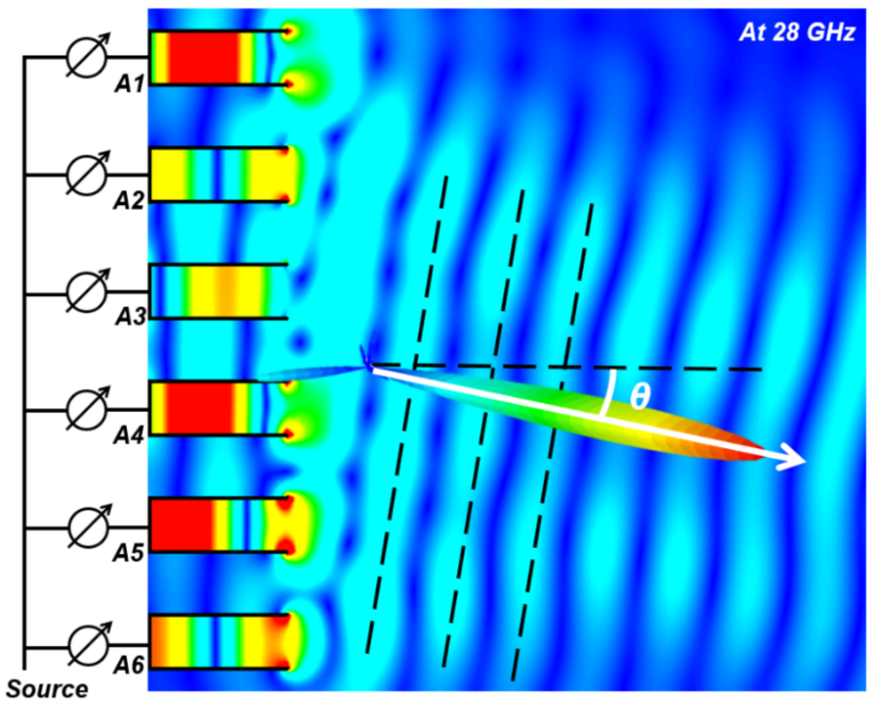

Figure 3: Simulated E-field plot at 28 GHz for a phased array antenna demonstrating beam-tilt.

Several such phased array antennas are widely shown in the literature. One of the most popular designs is a stacked array antenna. They are capable of generating highly directional tilted beams but are difficult to reconfigure. As an example, a 20 × 20 array of microstrip patch antennas with parasitic elements was presented in [20] to operate at 26 GHz with a half-power beamwidth (HPBW) of 5^{o} and a gain of 30 dBi. Similar techniques are seen frequently in the literature to generate a highly directional high gain beam with reduced sidelobe levels (SLL) at millimeter-wave bands [21]–[25].

Given phased arrays can generate a beam-tilt, several new techniques were explored to achieve a reconfigurable phase shift between the radiating elements. One simple method is providing an individual phase shifter to each radiating element, but it ends up being an extremely bulky and costly system. Such phase shifts can also be generated by a circuit-based feed network to a multi-antenna system to realize a beam-steering (or beam-switching) architecture. Two such popular architectures are known as Butler [26] and Nolen [27] matrices.

A conventional N $\times N$ Butler matrix can control an$N$- element array and generate N orthogonal beams through different phase distributions. The simplest form of a Butler matrix is designed using a 3 dB quadrature coupler and 45° phase shifters [28], [29]. Such matrices can be optimized for much larger antenna arrays and hence produce wide beam-steering. A complex 8×8 Butler matrix using eight tunable phase shifters was used with a phased array antenna to produce a beam-switching range of 108° with a beam resolution of 2° [26]. Various other works with cascaded Butler matrices are also presented in the literature to facilitate a two-dimensional beam-steering [30]–[34], see Figure 4. Unlike Butler matrices, a Nolen matrix uses couplers with different coefficients along with external phase shifters [35]. They have been demonstrated to be capable of creating multi-beam antenna arrays and 2D-beamforming [27], [36]–[38].

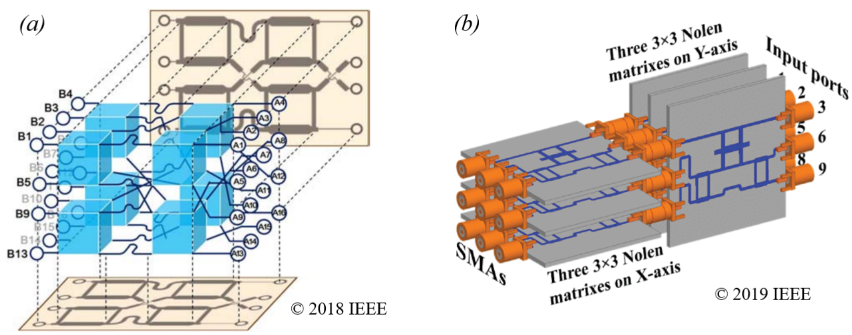

Figure 4: A two-dimensional beam-steering architecture of (a) Butler Matrix [34] and (b) Nolen Matrix [38].

Although such matrices are easy to design and implement, and then can provide a good degree of freedom in terms of customized EM beams for designated applications, they need a large form factor and hence increase the overall size and cost of manufacturing the antenna system.

Phased array antennas have seen significant development over the past few decades and are now being used extensively for different applications. They can provide a wide beam-steering with small form-factor; however, they are costly to manufacture and high-power consumption requirements which may not be ideal for mass deployment of the system.

Quasi-Optical Systems

As the name suggests, this technique uses different concepts of optics to generate beam reconfigurability. Three key methods in the literature includes use of Rotman lenses, Luneburg lenses and dielectric lenses (homogeneous and graded index), see Figure 5. This section will highlight some of the key developments in this subject with regard to achieving wide beam-steering for Beyond-5G applications.

A Rotman lens can be used as a feeder to a phased array antenna and similar to Butler matrix, it acts as a phase-shifting network [39]. Such a lens allows the generation of multiple beams simultaneously without the need of any active components. Such lenses have been used in the literature with different phased array antennas such as planar microstrip arrays [40]–[43], PCB-based endfire antennas [44], [45] and substrate-integrated waveguide based leaky-wave antennas [46], [47]. Rotman lenses provide good control on beam-reconfigurability, however, they add to the physical size of the antenna and require a multi-feed system. Several new architectures have been presented in the literature proposing variation in feeding style by creating a dual-layer model and hence, moving the lens at the bottom of the antenna instead of putting it adjacent [48]–[51]. This reduces the overall physical size of the antenna while keeping the volume consistent and is desirable for several applications. Rotman lenses are popularly used on aircrafts for satellite communications on the move [46].

Luneburg lenses, first introduced in 1944 [52], introduced the concepts of optics for RF applications. A conventional Luneburg lens is spherical in shape and has its relative permittivity varying from 2 in the center to 1 on the surface. Such lenses have their focal plane on the periphery of the spherical structure and are very popularly used to focus the beam in one direction. With the advancements in additive manufacturing [53], several modifications of the Luneburg lenses have been presented in the literature to achieve wide beam-steering capabilities [54]. One of the big issues with Luneburg lenses is its spherical shape, which makes it difficult to integrate planar feed antennas. Transformation optics was incorporated by [55], [56] to achieve a planar focal plane to such lenses and hence, achieve a wide beam-steering range [57]–[59]. Several other interesting works demonstrated miniaturization of Luneburg lenses with transformation optics and are now considered for applications in 5G/6G networks as well as satellite communications [60]–[62].

Luneburg lenses laid the foundation for dielectric lenses, and several different iterations of graded index [63]–[67], homogeneous [68]–[70], Fresnel [71]–[73] and geodesic lenses [74], [75] were presented in the literature with focus on converting spherical wavefronts into planar wavefronts, and hence, achieving high directionality [76], [77]. However, with the variation in feed-point, such lenses can also be used to generate multi-beam as well as beam-steering capabilities [78], [79].

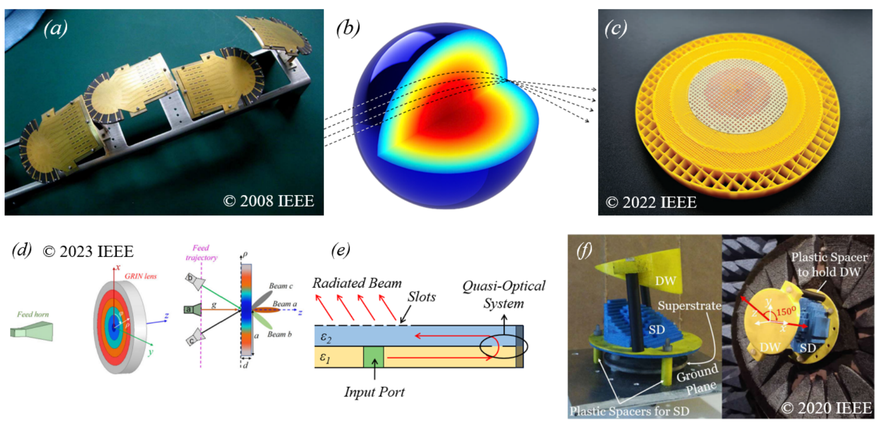

Figure 5: Different quasi-optical systems for beam-steering from literature: (a) Rotman lens array for beam-steering on aircrafts [46]; (b) 3D-representation of a spherical Luneburg lens; (c) a graded-index lens [53]; (d) representation of beam-steering using lenses [67]; (e) working principle of pillbox antennas [84]; (f) Risley prism based design for 2D beam-steering [82].

Another interesting quasi-optical technique for beam-steering involves the use of a pair of identical Risley prisms. With the rotation of each prism, the radiated beam can be deflected in different directions on a 2-D plane and is highly suitable for applications in 5G terrestrial networks [80]–[82]. The limitation of such beam-steering mechanisms is the need for physical rotation and the large volume of the overall structure.

Continuous transverse stub (CTS) or pillbox antennas are another class of antennas popularly seen in ground station applications that can also be modified for terrestrial networks [83]–[85]. These are dual-layered structures where the bottom layer consists of multiple feed points and the top layer consists of an array of radiating elements such as an SIW antenna or a phased array. The two layers are connected with a convex-shaped reflector created with metallic vias, and based on the feed position, the beam direction can be reconfigured.

Quasi-optical systems for beam-steering are highly efficient and can produce wide angle steering. They are cost-effective and can easily be manufactured with simple techniques such as additive manufacturing. However, they tend to be 3D structures with large volume and may not be suitable for every environment. Such quasi-optical systems are of great interest to both antenna engineers and material scientists to further reduce their physical size and make them suitable for practical applications in terrestrial networks.

Leaky-Wave Antennas

First introduced in 1950s [86], leaky-wave antennas (LWA) are popularly known for their beam-scanning capabilities. LWAs radiate because of the leakage of the travelling wave as it propagates through a guiding structure [87], [88]. LWAs generally have an inherent property of frequency-controlled beam-scanning, which means that the radiated beam direction changes with the change in operating frequency. This is because all the radiating elements in an LWA are fed sequentially, and with change in frequency, the inherent phase shift between radiating elements changes, which directly impacts the beam direction as shown in Figure 3.

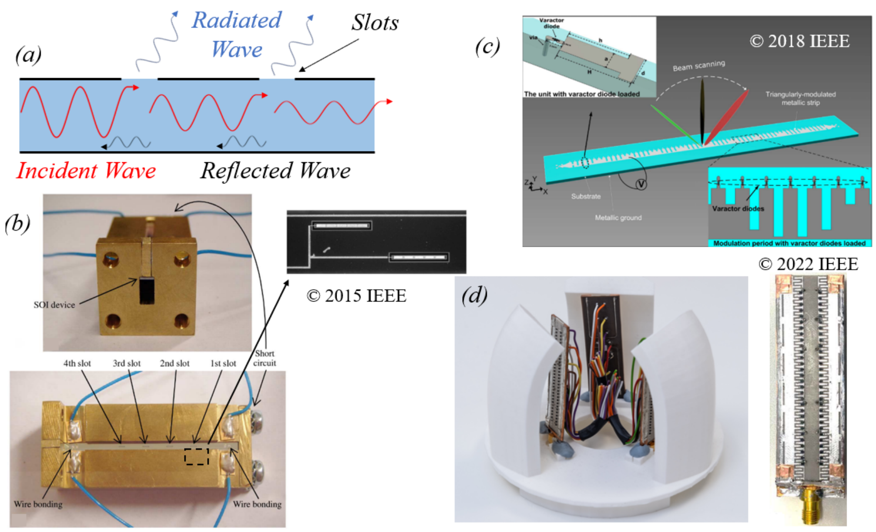

Figure 6: (a) Illustration of the working principle of an LWA; (b) dielectric-filled waveguide based LWA with doped p-i-n diodes [97]; (c) Modulated LWA on a microstrip guiding structure using varactors for beam-steering [98]; (d) a full 360° beam-steering antenna for a millimeter-wave 5G base-station [99] using three corrugated SIW-based LWAs [100].

Microstrip lines and substrate integrated waveguides (SIWs) are popularly used as the guiding structure for LWA [89], [90]. Microstrip guiding structures tend to be highly lossy because of the dielectric but allows easy fabrication and conformality. Waveguides, on the other hand, tend to be bulky and cannot be miniaturized. SIWs or dielectric filled waveguides (DFW) were introduced as intermediate solution to both the problems, where a low-profile rectangular waveguide is created with a dielectric substrate sandwiched between two conductive planes [91].

LWAs are divided into three categories: periodic, uniform, and quasi-uniform [92]. A uniform LWA has a single uniform slot along the structure and can only scan in the front quadrant. A quasi-uniform LWA is made up of closely placed radiating elements. Since these elements are placed very closely, it can be considered to be almost uniform, and hence, quasi-uniform. A periodic LWA, as the name suggests, has radiating elements arranged periodically. Such LWAs can scan a beam from backward to forward endfire direction [93]–[95]. Conventional periodic LWAs cannot scan the broadside of the antenna because of open stopband suppression [86] as the travelling wave starts acting as a standing wave at the broadside and all the reflections being in phase start creating an impedance mismatch. However, different techniques have been presented in the literature to enable this broadside scanning [93], [96].

Even though LWAs tend to change beam-direction with change in frequency, several innovative techniques have been introduced in the past to actively control this beam-steering using active components such as RF micro-electro-mechanical switches [101], p-i-n diodes [102]–[105], varactor diodes [98], [106], liquid crystals

[107], etc. One such work was presented by Yashchyshyn*et al* [97], [108] where a DFW's substrate material was doped at specific positions on the slots to create p-i-n diodes. The DFW was then controlled using bias lines to manipulate the current distribution on the guiding structure and generate beam-steering of ±45°.

Several such reconfigurable LWAs have been shown in the literature to generate active beam-steering using SIWs as the guiding structure [109]. SIWs are composed of hundreds of vias acting as electrical walls on a planar circuit, which not only makes the antenna rigid, but also costly to manufacture. To further add to it, it is difficult to attain DC biasing on a conventional SIW, and hence, making it difficult to implement diodes and related components. As a solution to this, Eccleston *et al* [110], [111] introduced corrugations as the replacement for vias in an SIW. The new corrugated SIW (CSIW) works within TE10 mode and can be used as new guiding structures for millimeter-wave antennas. Several iterations of such corrugated SIWs have been shown in the literature to achieve fixed frequency beam-steering. These include straight [112], bent [113], folded [114], half-mode [115] and twisted [116] corrugations. One such work upgraded the corrugations with inter-digitated capacitor design to achieve low transmission loss on the guiding structure and with the introduction of p-i-n diodes, the design demonstrated manipulation of surface currents, which was then used to achieve wide beam-steering in both azimuth and elevation planes [100], [117]. Finally, the new beam-steering CSIW was coupled with new lenses to generate a full 360° beam-steering base-station antenna for millimeter-wave 5G networks [99].

Leaky wave antennas are great planar structures which can achieve wide beam-steering and can be fabricated at low-cost. However, they will always have the inherent problem of frequency-controlled beam-scanning, which can either be used with resource reallocation methods or can be mitigated using new innovative techniques as described earlier in this section.

Metamaterials and Metasurfaces

Metamaterials and metasurfaces are one of the most popular topics in the realm of electromagnetics. Metamaterials are defined as artificial structures that are designed to exhibit specific electromagnetic properties that are not commonly found in nature [118]. Metamaterials have drawn great attention because of their ability to provide new materials with tunable permittivity, permeability, and refractive index. These materials can be used to redirect the beam in different directions [119]–[121], and hence, achieve a simple form of beam-steering. This beam-tilting can be understood through Snell's law and is described in detail within the Supplementary Information.

Metasurfaces are two-dimensional metamaterials composed of an array of meta-atoms and can be used to control the electromagnetic environment and redirect beam in different directions [122]. Frequency selective surfaces (FSS) can be considered as one of the primitive examples of such metasurfaces, and they are popularly seen to be used for a full 360° control of beam-control by placing small FSS sections across an omni-directional antenna.

Tunable FSS are used as reconfigurable filters, and when in the form of a superstrate or a radome and coupled with antennas, they can act as a frequency window and hence allow the beam to radiate in selected directions [123], [124], see Figure 7. Work presented in [125], [126] used hexagonal structures for dielectric resonator antennas with FSS that allowed six beams to be generated in the azimuth plane and two beams in the elevation plane, and hence, giving a 2D beam-steering mechanism. The design used a cantilever mechanism to generate a tunable FSS, where a change in the height of cantilever introduced variation in capacitance and hence the band-pass frequency. This change would only allow the beam to radiate through the FSS in a specific direction, while blocking it in every other direction. Superstrates consisting of reconfigurable FSS and partially reflective surfaces (PRS) with active components can also provide a similar behavior [127]–[131]. PRS can also be used to create a Fabry-Perot cavity and generate beam-reconfigurability [132], [133].

Besides tunable FSS, the metasurface community has been growing significantly to create reconfigurable intelligent surfaces (RIS) that can act as either transmit-arrays or reflect-arrays. Such RIS can be reconfigured using a pre-defined codebook to change the beam-direction of an incident wave with minimal losses. This change in beam direction occurs because of the change in surface currents of the incident electromagnetic wave induced by the phase profile of the metasurface. RIS as a superstrate to the antennas can be used to achieve both beam-steering as well as multi-beam generation with a single feeder. Several such designs have been presented in the literature that use intelligent metasurfaces as either a reflector or a transmit-array to attain reconfigurability [134]–[140], see Figure 7.

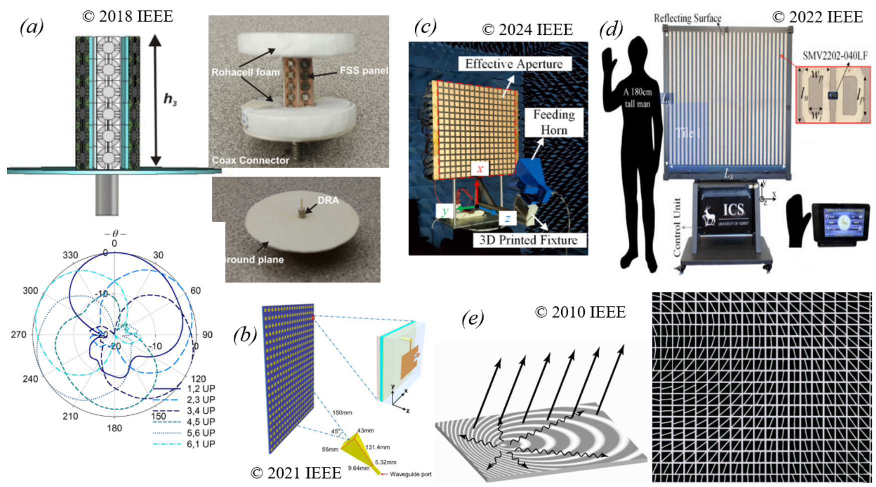

Figure 7: (a) Cantilever-based FSS around a dielectric resonator antenna for 360° beam-steering [126]; (b) an illustration of an active reconfigurable metasurface for beam-steering [140]; (c) a reconfigurable reflectarray for beam-steering [136]; (d) a full sub-6 GHz RIS for smart electromagnetic environments [141]; (e) working principle of a holographic metasurface and layout for a holographic metasurface [142].

RIS are also being proposed as an inherent component for the new Beyond-5G infrastructure and will be used to control the electromagnetic environment [143]. Several such RIS for current sub-6 GHz 5G network have been demonstrated and verified in an indoor and outdoor setting [141], [144], [145]. These intelligent surfaces use thousands of active components such as p-i-n diodes and varactors. Their overall power consumption is low ($<$ 15 W for p-i-n diode based RIS and $<$ 15 mW for varactor-based RIS). However, they need regular power consumption which increases their overall energy consumption considerably. To add to this, when we redesign these structures for millimeter-wave bands for Beyond-5G networks, the number of p-i-n diodes are multiplied by a factor of at least 50 (assuming an $> 7\times$ frequency scaling), increasing the power consumption, fabrication cost, and complexity by the same ratio [146].

Holography is another very interesting technique that has been shown in the literature to convert an omnidirectional beam pattern to a highly directional antenna. Such metasurfaces are known as holographic metasurfaces, and they use the surface waves generated by an omnidirectional feed and manipulate the flow along the surface to radiate in a stipulated direction [147]. Several such holographic metasurfaces have been presented in the literature that can be used to generate multi-beam characteristics and reconfigure the beam-direction at will [148], [149], see Figure 7.

Different variations of metasurfaces are seen in the literature to generate fast beam-steering capabilities for Beyond-5G networks. Such metasurfaces can generate highly directional high gain simultaneous multi-beam characteristics and hence, are highly desirable. However, they tend to have a large form-factor, are power hungry and can be expensive. Furthermore, such metasurfaces are generally narrow-band, and they act as a reflector at other frequencies. This means, if the metasurface operates at 26 GHz in the UK at 5G network, it will start shadowing the sub-6 GHz network. Without careful design, this may not be desirable.

Table 1: Summary of different capabilities of the four categories of beam-steering antennas.

	Phased Array Antennas	Quasi-Optical System	Leaky-Wave
Bandwidth	Wideband	Wideband	Wideband, but
Implementation	Planar design	3D design	Planar design
Fabrication	PCB etching with active elements	Additive manufacturing and PCB etching	PCB etching
Design Complexity	Moderate	Low	Low
Fabrication Cost	Moderate	Low	Low
Power Requirements	Moderate	Low	Low
Beam-Steering Range	Moderate	Wide	Moderate

Conclusion

Beam-steering is a key enabler for millimeter-wave terrestrial networks. With the introduction of 5G-Advanced and 6G networks in the coming years, commercialization of beam-steering antennas will enable the telecommunication industry to establish a new network infrastructure. We can classify beam-steering antennas for such networks into four categories as described in this article. These are (i) phased array antennas, (ii) quasi-optical systems, (iii) leaky-wave antennas, and (iv) metamaterials and metasurfaces. Each of these categories has their own set of merits and demerits in terms of complexity, bandwidth, cost, power requirements, and beam-steering capabilities. Table 1 compares and summarizes the four categories with these parameters. Even though beam-steering antenna technology has advanced significantly over time, there are still some key challenges that need to be addressed before they get incorporated into the network. To highlight a few, these challenges include (i) high complexity, cost of fabrication and power requirements for intelligent metasurfaces, (ii) out-of-band shadowing because of metasurfaces, (iii) power requirements of phased array antennas, and (iv) mass production of 3D-printed quasi-optical systems. Additional figures and links to videos can be found in the Supplementary Information.

References

[1] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, "Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks-With a Focus on Propagation Models," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12. Institute of Electrical and Electronics Engineers Inc., pp. 6213–6230, Dec. 01, 2017. doi: 10.1109/TAP.2017.2734243. [2] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011, doi: 10.1109/MCOM.2011.5783993. [3] T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access*, vol. 1, pp. 335–349, 2013, doi: 10.1109/ACCESS.2013.2260813. [4] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-wave propagation channel characterization for short-range wireless communications," *IEEE Trans. Veh. Technol.*, vol. 58, no. 1, pp. 3–13, 2009, doi: 10.1109/TVT.2008.924990. [5] N. P. Narekar and D. M. Bhalerao, "A survey on obstacles for 5G communication," in *International Conference on Communication and Signal Processing, ICCSP*, Institute of Electrical and Electronics Engineers Inc., Nov. 2015, pp. 831–835. doi: 10.1109/ICCSP.2015.7322610. [6] Z. A. Shamsan, "Rainfall and Diffraction Modeling for Millimeter-Wave Wireless Fixed Systems," *IEEE Access*, vol. 8, pp. 212961–212978, 2020, doi: 10.1109/ACCESS.2020.3040624. [7] G. R. Maccartney, J. Zhang, S. Nie, and T. S. Rappaport, "Path loss models for 5G millimeter wave propagation channels in urban microcells," in *GLOBECOM - IEEE Global Telecommunications Conference*, Institute of Electrical and Electronics Engineers Inc., 2013, pp. 3948–3953. doi: 10.1109/GLOCOM.2013.6831690. [8] K. W. Kim, M. D. Kim, J. Lee, J. J. Park, Y. K. Yoon, and Y. J. Chong, "Millimeter-wave diffraction-loss model based on over-rooftop propagation measurements," *ETRI*

J., vol. 42, no. September 2019, pp. 827–836, 2020, doi: 10.4218/etrij.2019-0411. [9] T. S. Rappaport, G. R. MacCartney, S. Sun, H. Yan, and S. Deng, "Small-Scale, Local Area, and Transitional Millimeter Wave Propagation for 5G Communications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6474–6490, Dec. 2017, doi: 10.1109/TAP.2017.2734159. [10] P. Zhang, B. Yang, C. Yi, H. Wang, and X. You, "Measurement-Based 5G Millimeter-Wave Propagation Characterization in Vegetated Suburban Macrocell Environments," *IEEE Trans. Antennas Propag.*, vol. 68, no. 7, pp. 5556–5567, 2020, doi: 10.1109/TAP.2020.2975365. [11] M. K. Samimi and T. S. Rappaport, "Local multipath model parameters for generating 5G millimeter-wave 3GPP-like channel impulse response," in *10th European Conference on Antennas and Propagation, EuCAP*, Institute of Electrical and Electronics Engineers Inc., May 2016. doi: 10.1109/EuCAP.2016.7481410. [12] H. M. Rahim, C. Y. Leow, T. A. Rahman, A. Arsad, and M. A. Malek, "Foliage Attenuation Measurement at Millimeter Wave Frequencies in Tropical Vegetation," in *IEEE 13th Malaysia International Conference on Communications*, Malaysia, 2017, pp. 241–246. [13] Z. Qingling and J. Li, "Rain Attenuation in Millimeter Wave Ranges," in *7th International Symposium on Antennas, Propagation & EM Theory*, 2006. [14] W. Roh *et al.*, "Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 106–113, 2014. [15] Y. N. R. Li, B. Gao, X. Zhang, and K. Huang, "Beam Management in Millimeter-Wave Communications for 5G and beyond," *IEEE Access*, vol. 8, pp. 13282–13293, 2020, doi: 10.1109/ACCESS.2019.2963514. [16] Y. Azar *et al.*, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," in *IEEE International Conference on Communications (ICC)*, 2013, pp. 5143–5147. [17] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, 2014, doi: 10.1109/MCOM.2014.6736761. [18] J. N. Murdock, E. Ben-Dor, Y. Qiao, J. I. Tamir, and T. S. Rappaport, "A 38 GHz Cellular Outage Study for an Urban Outdoor Campus Environment," in *IEEE Wireless Communications and Networking Conference*, IEEE, 2012, pp. 3085–3090. [19] E. Bruce and A. C. Beck, "Experiments with Directivity Steering for Fading Reduction," *Bell Syst. Tech. J.*, vol. 14, no. 2, pp. 195–210, 1935, doi: 10.1002/j.1538-7305.1935.tb00412.x. [20] S. Oh, S. Seo, M. Yoon, C. Oh, E. Kim, and Y. Kim, "A Broadband Microstrip Antenna Array for LMDS Applications," *Microwave and Optical Technology Letters*, vol. 32, no. 1, pp. 35-37, 2002. [21] K. Wincza and S. Gruszczynski, "Microstrip antenna arrays fed by a series-parallel slot-coupled feeding network," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 991–994, 2011, doi: 10.1109/LAWP.2011.2167491. [22] Z. Chen and S. Otto, "A Taper Optimization for Pattern Synthesis of Microstrip Series-Fed Patch Array Antennas," in *2nd European Wireless Technology Conference*, 2009, pp. 160–163. [23] P. A. Dzagbletey, K. S. Kim, W. J. Byun, and Y. B. Jung, "Stacked microstrip linear array with highly suppressed side-lobe levels and wide bandwidth," *IET Microwaves, Antennas Propag.*, vol. 11, no. 1, pp. 17–22, Jan. 2017, doi: 10.1049/iet-map.2016.0161. [24] P. A. Dzagbletey and Y. B. Jung, "Stacked microstrip linear array for millimeter-wave 5G baseband communication," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 5, pp. 780–783, May 2018, doi: 10.1109/LAWP.2018.2816258. [25] M. Khalily, R. Tafazolli, T. A. Rahman, and M. R. Kamarudin, "Design of Phased Arrays of Series-Fed Patch Antennas with Reduced Number of the Controllers for 28-GHz mm-Wave Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 15, pp. 1305–1308, 2016, doi: 10.1109/LAWP.2015.2505781. [26] C. C. Chang, R. H. Lee, and T. Y. Shih, "Design of a beam switching/steering butler matrix for phased array system," *IEEE Trans. Antennas Propag.*, vol. 58, no. 2, pp. 367–374, Feb. 2010, doi: 10.1109/TAP.2009.2037693. [27] J. Z. Cao and F. C. Chen, "Design of Continuously Steerable Nolen Matrix-Based Beamforming Networks Using Tunable Phase Shifters," *2022 Int. Conf. Microw. Millim. Wave Technol. ICMMT 2022 - Proc.*, pp. 1–3, 2022, doi: 10.1109/ICMMT55580.2022.10023059. [28] S. Z. Ibrahim and M. E. Bialkowski, "Wideband Butler Matrix in Microstrip-Slot Technology," in *Asia Pacific Microwave Conference*, IEEE, 2009, pp. 2104–2107. [29] G. Breed, "Transmission Line and Lumped Element Quadrature Couplers," *High Frequency Electronics*, pp. 44–48, 2009. [30] X. Wang, X. Fang, M. Laabs, and D. Plettemeier, "Compact 2-D multibeam array antenna fed by planar cascaded butler matrix for millimeter-wave communication," *IEEE Antennas Wirel. Propag. Lett.*, vol. 18, no. 10, pp. 2056–2060, 2019, doi: 10.1109/LAWP.2019.2937254. [31] D. Wang, E. Polat, H. Tesmer, H. Maune, and R. Jakoby, "Switched and Steered Beam End-Fire Antenna Array Fed by Wideband Via-Less Butler Matrix and Tunable Phase Shifters Based on Liquid Crystal Technology," *IEEE Trans. Antennas Propag.*, vol. 70, no. 7, pp. 5383–5392, 2022, doi: 10.1109/TAP.2022.3142334. [32] H. So *et al.*, “Staircase Array Antenna with Stacked Butler Matrix for Concurrent Multi-Beams,” *IEEE Access*, vol. 11, no. July, pp. 76638–76646, 2023, doi: 10.1109/ACCESS.2023.3297659. [33] A. Abhishek, Z. Zeya, P. Suraj, and R. K. Badhai, “Design of beam steering antenna for 5G at 28GHz using butler matrix,” *Proc. 2020 Int. Conf. Comput. Commun. Secur. ICCCS 2020*, vol. 79, pp. 28–31, 2020, doi: 10.1109/ICCCS49678.2020.9276492. [34] K. Ding and A. Kishk, “Two-Dimensional Butler Matrix Concept for Planar Array,” *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 2018-June, pp. 632–635, 2018, doi: 10.1109/MWSYM.2018.8439616. [35] B. W. Xu, Y. Yang, S. Y. Zheng, and W. Che, “Single-/Dual-Beam Switchable Beamforming Network Based on Phase-Shifter-Relaxed 4×4 Nolen Matrix,” *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 518–530, 2024, doi: 10.1109/TAP.2023.3326833. [36] N. S. Mohd Suhaimi and N. M. Mahyuddin, “Review of Switched Beamforming Networks for Scannable Antenna Application towards Fifth Generation (5G) Technology,” *Int. J. Integr. Eng.*, vol. 12, no. 6, pp. 62–70, 2020, doi: 10.30880/ijie.2020.12.06.008. [37] J. Z. Cao and F. C. Chen, “A Tunable Nolen Matrix Based on Reconfigurable Phase Shifters,” *13th Int. Symp. Antennas, Propag. EM Theory, ISAPE 2021 - Proc.*, vol. Volume1, pp. 1–3, 2021, doi: 10.1109/ISAPE54070.2021.9752958. [38] H. Ren, H. Zhang, Y. Jin, Y. Gu, and B. Arigong, “A Novel 2-D 3 X 3 Nolen Matrix for 2-D Beamforming Applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 67, no. 11, pp. 4622–4631, 2019, doi: 10.1109/TMTT.2019.2917211. [39] W. Rotman and R. F. Turner, “Wide-Angle Microwave Lens for Line Source Applications,” *IEEE Trans. Antennas Propag.*, vol. 11, no. 6, pp. 623–632, 1963, doi: 10.1109/TAP.1963.1138114. [40] J. Li, C. He, H. Fan, and R. Jin, “Gain-Equalized Multibeam Antenna Fed by a Compact Dual-Layer Rotman Lens at Ka-Band,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 2307–2311, 2022. [41] A. Azari, A. Skrivervik, and H. Aliakbarian, “Design of a novel wide-angle Rotman lens beamformer for 5G mmWave applications,” *Sci. Rep.*, vol. 14, no. 1, pp. 1–15, 2024, doi: 10.1038/s41598-024-51733-0. [42] S. K. Karki *et al.*, “Beam-Reconfigurable Antenna Based on Vector Modulator and Rotman Lens on LTCC,” *IEEE Access*, vol. 9, pp. 52872–52882, 2021, doi: 10.1109/ACCESS.2021.3070037. [43] E. Tolin, O. Litschke, S. Bruni, and F. Vipiana, “Compact Extended Scan Range Antenna Array Based on Rotman Lens,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 12, pp. 7356–7367, 2019, doi: 10.1109/TAP.2019.2935086. [44] M. Heino, C. Icheln, J. Haarla, and K. Haneda, “PCB-Based Design of a Beamsteerable Array with High-Gain Antennas and a Rotman Lens at 28 GHz,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 10, pp. 1754–1758, Oct. 2020, doi: 10.1109/LAWP.2020.3017129. [45] Y. Yu, H. Luyen, and N. Behdad, “A wideband millimeter-wave rotman lens multibeam array using substrate integrated coaxial line (SICL) technology,” *IEEE Trans. Antennas Propag.*, vol. 69, no. 11, pp. 7532–7542, 2021, doi: 10.1109/TAP.2021.3090518. [46] Y. J. Cheng *et al.*, “Substrate integrated waveguide (SIW) Rotman lens and its Ka-band multibeam array antenna applications,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 8 II, pp. 2504–2513, 2008, doi: 10.1109/TAP.2008.927567. [47] J. W. Lian, Y. L. Ban, H. Zhu, and Y. J. Guo, “Reduced-Sidelobe Multibeam Array Antenna Based on SIW Rotman Lens,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 1, pp. 188–192, Jan. 2020, doi: 10.1109/LAWP.2019.2957509. [48] K. Tekkouk, M. Ettorre, L. Le Coq, and R. Sauleau, “Multibeam SIW Slotted Waveguide Antenna System Fed by a Compact Dual-Layer Rotman Lens,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 504–514, Feb. 2016, doi: 10.1109/TAP.2015.2499752. [49] Y. Liu, H. Yang, Z. Jin, F. Zhao, and J. Zhu, “A Multibeam Cylindrically Conformal Slot Array Antenna Based on a Modified Rotman Lens,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3441–3452, 2018, doi: 10.1109/TAP.2018.2829816. [50] J. Y. Deng, Y. Bin Liu, Z. Chen, and W. Lin, “Compact Multibeam Antenna Using Miniaturized Slow-Wave Substrate-Integrated Waveguide Rotman Lens for Satellite-Assisted Internet of Vehicles,” *IEEE Internet Things J.*, vol. 11, no. 4, pp. 6848–6856, 2024, doi: 10.1109/JIOT.2023.3313309. [51] Q. Liang, B. Sun, and G. Zhou, “Miniaturization of Rotman Lens Using Array Port Extension,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 22, no. 3, pp. 541–545, 2023, doi: 10.1109/LAWP.2022.3217399. [52] R. K. Luneburg, *Mathematical Theory of Optics.* RI, USA: Brown University Press, 1944. [53] T. Whittaker, S. Zhang, C. Stevens, A. Powell, J. C. Vardaxolgou, and W. G. Whittow, “3D Printing Materials and Techniques for Antennas and Metamaterials,” *IEEE Antennas Propag. Mag.*, pp. 2–12, 2022, doi: 10.1109/MAP.2022.3229298. [54] B. Zhou, Y. Yang, H. Li, and T. J. Cui, “Beam-steering Vivaldi antenna based on partial Luneburg lens constructed with composite materials,” *J. Appl. Phys.*, vol. 110, no. 8, Oct. 2011, doi: 10.1063/1.3651376. [55] J. Yi, S. N. Burokur, and A. de Lustrac, "Conceptual design of a beam steering lens through transformation electromagnetics," *Opt. Express*, vol. 23, no. 10, p. 12942, May 2015, doi: 10.1364/oe.23.012942. [56] N. B. Kundtz, D. R. Smith, and J. B. Pendry, "Electromagnetic design with transformation optics," *Proceedings of the IEEE*, vol. 99, no. 10. Institute of Electrical and Electronics Engineers Inc., pp. 1622–1633, 2011. doi: 10.1109/JPROC.2010.2089664. [57] A. Bansal, H. Nagi, P. Febvre, and W. Whittow, "Bespoke Luneburg Lens for Two-Dimensional Beam-Steering Antennas for SatComms on the Move," *IEEE Int. Symp. Antennas Propag. Usn. Radio Sci. Meet.*, pp. 733–734, 2023, doi: 10.1109/USNC-URSI52151.2023.10238014. [58] A. Bansal, E. Mellios, H. Nagi, P. Febvre, and W. G. Whittow, "Two-Dimensional Beam-Steering Lens Antenna with Fast Inter-Beam Handover for PNT and Data Services for Satellite Communications on the Move," *TechRxiv Prepr.*, 2023, doi: https://doi.org/10.36227/techrxiv.24157410.v1. [59] J. G. Marin and J. Hesselbarth, "Lens Antenna with Planar Focal Surface for Wide-Angle Beam-Steering Application," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2757–2762, 2019. [60] N. Nikolic and A. Hellicar, "Fractional Luneburg lens antenna," *IEEE Antennas Propag. Mag.*, vol. 56, no. 5, pp. 116–130, Oct. 2014, doi: 10.1109/MAP.2014.6971923. [61] O. Zetterstrom, N. J. G. Fonseca, and O. Quevedo-Teruel, "Compact Half-Luneburg Lens Antenna Based on a Glide-Symmetric Dielectric Structure," *IEEE Antennas Wirel. Propag. Lett.*, vol. 1, pp. 1–5, 2022, doi: 10.1109/LAWP.2022.3179639. [62] H. Giddens, A. S. Andy, and Y. Hao, "Multimaterial 3-D Printed Compressed Luneburg Lens for mm-Wave Beam Steering," *IEEE Antennas Wirel. Propag. Lett.*, vol. 20, no. 11, pp. 2166–2170, 2021, doi: 10.1109/LAWP.2021.3109591. [63] S. Zhang, R. K. Arya, S. Pandey, Y. Vardaxoglou, W. Whittow, and R. Mittra, "3D-printed planar graded index lenses," *IET Microwaves, Antennas Propag.*, vol. 10, no. 13, pp. 1411–1419, Oct. 2016, doi: 10.1049/iet-map.2016.0013. [64] S. Zhang, R. K. Arya, W. G. Whittow, D. Cadman, R. Mittra, and J. C. Vardaxoglou, "Ultra-Wideband Flat Metamaterial GRIN Lenses Assisted with Additive Manufacturing Technique," *IEEE Trans. Antennas Propag.*, vol. 69, no. 7, pp. 3788–3799, Jul. 2021, doi: 10.1109/TAP.2020.3044586. [65] W. Shao and Q. Chen, "2-D Beam-Steerable Generalized Mikaelian Lens with Unique Flat-Shape Characteristic," *IEEE Antennas Wirel. Propag. Lett.*, vol. 20, no. 10, pp. 2033–2037, 2021, doi: 10.1109/LAWP.2021.3102316. [66] S. Jain, M. Abdel-Mageed, and R. Mittra, "Flat-lens design using field transformation and its comparison with those based on transformation optics and ray optics," *IEEE Antennas Wirel. Propag. Lett.*, vol. 12, pp. 777–780, 2013, doi: 10.1109/LAWP.2013.2270946. [67] L. Z. Song, M. Ansari, P. Y. Qin, S. Maci, J. Du, and Y. J. Guo, "Two-Dimensional Wide-Angle Multibeam Flat GRIN Lens with a High Aperture Efficiency," *IEEE Trans. Antennas Propag.*, vol. 71, no. 10, pp. 8018–8029, 2023, doi: 10.1109/TAP.2023.3298143. [68] A. Bansal, C. J. Panagamuwa, and W. Whittow, "Novel Design Methodology for 3D-Printed Lenses for Travelling Wave Antennas," *IEEE Open J. Antennas Propag.*, vol. 4, no. January, pp. 196–206, 2023, doi: 10.1109/OJAP.2023.3243408. [69] Y. Luo and Z. N. Chen, "A Scanning Angle Range Enhanced Phased Array Antenna Using Concave-Convex Lens," *Proc. 2018 IEEE Int. Conf. Serv. Oper. Logist. Informatics, SOLI 2018*, pp. 17–20, 2018, doi: 10.1109/SOLI.2018.8476789. [70] A. O. Diallo, R. Czarny, B. Loiseaux, and S. Hole, "Comparison between a Thin Lens Antenna Made of Structured Dielectric Material and Conventional Lens Antennas, in Q-Band in a Compact Volume," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 2, pp. 307–310, Feb. 2018, doi: 10.1109/LAWP.2017.2787789. [71] M. R. D. Kodnoeih, Y. Letestu, R. Sauleau, E. M. Cruz, and A. Doll, "Compact folded fresnel zone plate lens antenna for mm-wave communications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 5, pp. 873–876, May 2018, doi: 10.1109/LAWP.2018.2820420. [72] J. M. Monkevich and G. P. Le Sage, "Design and Fabrication of a Custom-Dielectric Fresnel Multi-Zone Plate Lens Antenna Using Additive Manufacturing Techniques," *IEEE Access*, vol. 7, pp. 61452–61460, 2019, doi: 10.1109/ACCESS.2019.2916077. [73] G. B. Wu, Y. S. Zeng, K. F. Chan, S. W. Qu, and C. H. Chan, "3-D Printed Circularly Polarized Modified Fresnel Lens Operating at Terahertz Frequencies," *IEEE Trans. Antennas Propag.*, vol. 67, no. 7, pp. 4429–4437, Jul. 2019, doi: 10.1109/TAP.2019.2908110. [74] Q. Liao, N. J. G. Fonseca, M. Camacho, A. Palomares-Caballero, F. Mesa, and O. Quevedo-Teruel, "Ray-Tracing Model for Generalized Geodesic-Lens Multiple-Beam Antennas," *IEEE Trans. Antennas Propag.*, vol. 71, no. 3, pp. 2640–2651, 2023, doi: 10.1109/TAP.2022.3233643. [75] O. Quevedo-Teruel *et al.*, "Geodesic Lens Antennas for 5G and beyond," *IEEE Commun. Mag.*, vol. 60, no. 1, pp. 40–45, 2022, doi: 10.1109/MCOM.001.2100545. [76] I. Munina, I. Grigoriev, G. O'Donnell, and D. Trimble, "A Review of 3D Printed Gradient Refractive Index Lens Antennas," *IEEE Access*, vol. 11, no. December 2022, pp. 8790–8809, 2023, doi: 10.1109/ACCESS.2023.3239782.

[77] A. Bansal, C. J. Panagamuwa, and W. G. Whittow, “Simplified Design Methodology for RF Dielectric Homogeneous and Graded Index Lenses,” in *IEEE Microwave, Antennas and Propagation Conference (MAPCON)*, Ahmedabad, India, 2023. [78] Y. J. Guo, M. Ansari, R. W. Ziolkowski, and N. J. G. Fonseca, “Quasi-Optical Multi-Beam Antenna Technologies for B5G and 6G mmWave and THz Networks: A Review,” *IEEE Open J. Antennas Propag.*, vol. 2, no. May, pp. 807–830, 2021, doi: 10.1109/OJAP.2021.3093622. [79] S. Huang, K. Y. Chan, and R. Ramer, “All 3-D Printed Antennas Based on Phase Velocity Control for Beam Steering and Size Reduction with Low Cost,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 1776–1786, 2022, doi: 10.1109/TAP.2021.3118777. [80] M. U. Afzal, K. P. Esselle, and M. N. Y. Koli, “A Beam-Steering Solution with Highly Transmitting Hybrid Metasurfaces and Circularly Polarized High-Gain Radial-Line Slot Array Antennas,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 1, pp. 365–377, 2022, doi: 10.1109/TAP.2021.3111522. [81] H. Lei *et al.*, “A Low-Profile Risley-Prism-Based 2-D Beam-Scanning Circularly Polarized Folded Transmitarray Antenna at Ku-Band,” *IEEE Trans. Antennas Propag.*, vol. 71, no. 7, pp. 6173–6178, 2023, doi: 10.1109/TAP.2023.3269102. [82] M. U. Afzal, L. Matekovits, K. P. Esselle, and A. Lalbakhsh, “Beam-scanning antenna based on near-electric field phase transformation and refraction of electromagnetic wave through dielectric structures,” *IEEE Access*, vol. 8, pp. 199242–199253, 2020, doi: 10.1109/ACCESS.2020.3033284. [83] M. Ettorre, F. F. Manzillo, M. Casaletti, R. Sauleau, L. Le Coq, and N. Capet, “Continuous Transverse Stub Array for Ka-Band Applications,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4792–4800, 2015, doi: 10.1109/TAP.2015.2479243. [84] M. Ettorre, R. Sauleau, and L. Le Coq, “Multi-beam multi-layer leaky-wave SIW pillbox antenna for millimeter-wave applications,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 4, pp. 1093–1100, Apr. 2011, doi: 10.1109/TAP.2011.2109695. [85] T. Potelon, M. Ettorre, L. Le Coq, T. Bateman, J. Francey, and R. Sauleau, “Reconfigurable CTS Antenna Fully Integrated in PCB Technology for 5G Backhaul Applications,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3609–3618, 2019, doi: 10.1109/TAP.2019.2902644. [86] J. L. Volakis, *Antenna Engineering Handbook*. McGraw-Hill, 2007. [Online]. Available: www.digitalengineeringlibrary.com [87] D. R. Jackson, C. Caloz, and T. Itoh, “Leaky-Wave Antennas,” *Proc. IEEE*, vol. 100, no. 7, pp. 2194–2206, 2012. [88] F. Monticone and A. Alù, “Leaky-wave theory, techniques, and applications: From microwaves to visible frequencies,” *Proc. IEEE*, vol. 103, no. 5, pp. 793–821, May 2015, doi: 10.1109/JPROC.2015.2399419. [89] G. Venanzoni, D. Mencarelli, A. Morini, M. Farina, and F. Prudenzano, “Review of substrate integrated-waveguide circuits for beam-forming networks working in x-band,” *Applied Sciences (Switzerland)*, vol. 9, no. 5. MDPI AG, pp. 1–19, 2019. doi: 10.3390/app9051003. [90] K. Wu, M. Bozzi, and N. J. G. Fonseca, “Substrate Integrated Transmission Lines: Review and Applications,” *IEEE J. Microwaves*, vol. 1, no. 1, pp. 345–363, Jan. 2021, doi: 10.1109/jmw.2020.3034379. [91] M. Bozzi, A. Georgiadis, and K. Wu, “Review of substrate-integrated waveguide circuits and antennas,” *IET Microwaves, Antennas Propag.*, vol. 5, no. 8, pp. 909–920, Jun. 2011, doi: 10.1049/iet-map.2010.0463. [92] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd Editio. New York, NY, USA: Wiley, 2005. [93] D. K. Karmokar, S. L. Chen, D. Thalakotuna, P. Y. Qin, T. S. Bird, and Y. J. Guo, “Continuous Backward-to-Forward Scanning 1-D Slot-Array Leaky-Wave Antenna with Improved Gain,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 1, pp. 89–93, Jan. 2020, doi: 10.1109/LAWP.2019.2953927. [94] S. Sengupta, D. R. Jackson, A. T. Almutawa, H. Kazemi, F. Capolino, and S. A. Long, “A Cross-Shaped 2-D Periodic Leaky-Wave Antenna,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1289–1301, Mar. 2020, doi: 10.1109/TAP.2019.2948524. [95] Y. Geng, J. Wang, Z. Li, Y. Li, M. Chen, and Z. Zhang, “Dual-Beam and Tri-Band SIW Leaky-Wave Antenna with Wide Beam Scanning Range including Broadside Direction,” *IEEE Access*, vol. 7, pp. 176361–176368, 2019, doi: 10.1109/ACCESS.2019.2957763. [96] Z. Ahmed, M. H. Hoang, P. McEvoy, and M. J. Ammann, “Millimetre-wave planar bruce array antenna,” in *2020 International Workshop on Antenna Technology, iWAT 2020*, Institute of Electrical and Electronics Engineers Inc., Feb. 2020. doi: 10.1109/iWAT48004.2020.1570608201. [97] G. Bogdan, K. Godziszewski, Y. Yashchyshyn, C. H. Kim, and S. B. Hyun, “Time-Modulated Antenna Array for Real-Time Adaptation in Wideband Wireless Systems-Part I: Design and Characterization,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 10, pp. 6964–6972, Oct. 2020, doi: 10.1109/TAP.2019.2902755. [98] M. Wang, H. F. Ma, H. C. Zhang, W. X. Tang, X. R. Zhang, and T. J. Cui, “Frequency-Fixed Beam-Scanning Leaky-Wave Antenna Using Electronically Controllable Corrugated Microstrip Line,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4449–4457, Sep. 2018, doi: 10.1109/TAP.2018.2845452. [99] A. Bansal, C. J.

Panagamuwa, and W. G. Whittow, “Full 360 ° beam steering millimetre-wave leaky-wave antennas coupled with bespoke 3D-printed dielectric lenses for 5G base stations,” *Electron. Lett.*, vol. 59, no. 8, pp. 5–7, 2023. [100] A. Bansal, C. Panagamuwa, and W. Whittow, “Millimeter-Wave Beam Steerable Slot Array Antenna Using an Inter-Digitated Capacitor Based Corrugated SIW,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 11761–11770, 2022, doi: 10.1109/TAP.2022.3211013. [101] L. Y. Ma, N. Soin, M. H. M. Daut, and S. F. W. M. Hatta, “Comprehensive Study on RF-MEMS Switches Used for 5G Scenario,” *IEEE Access*, vol. 7, pp. 107506–107522, 2019, doi: 10.1109/ACCESS.2019.2932800. [102] T. Lou, X. X. Yang, H. Qiu, Q. Luo, and S. Gao, “Low-Cost Electrical Beam-Scanning Leaky-Wave Antenna Based on Bent Corrugated Substrate Integrated Waveguide,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 18, no. 2, pp. 353–357, Feb. 2019, doi: 10.1109/LAWP.2019.2890995. [103] I. Serhsouh, M. Himdi, H. Lebbar, and H. Vettikalladi, “Reconfigurable SIW Antenna for Fixed Frequency Beam Scanning and 5G Applications,” *IEEE Access*, vol. 8, pp. 60084–60089, 2020, doi: 10.1109/ACCESS.2020.2983001. [104] D. K. Karmokar, K. P. Esselle, and S. G. Hay, “Fixed-Frequency Beam Steering of Microstrip Leaky-Wave Antennas Using Binary Switches,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2146–2154, Jun. 2016, doi: 10.1109/TAP.2016.2546949. [105] A. Bansal, C. J. Panagamuwa, and W. G. Whittow, “Fixed frequency beam-steering using bow-tie slot based dielectric filled waveguide antenna array,” *Electron. Lett.*, vol. 59, no. 13, pp. 1–3, 2023, doi: 10.1049/ell2.12864. [106] J. L. Gomez-Tornero, R. Guzman-Quiros, G. Goussetis, and S. K. Podilchak, “Electronically-reconfigurable parallel-plate wave launchers based on corrugated substrate integrated leaky waveguides with tunable components,” in *46th European Microwave Conference*, Institute of Electrical and Electronics Engineers Inc., 2016, pp. 795–798. doi: 10.1109/EuMC.2016.7824463. [107] D. Jiang *et al.*, “Liquid crystal-based wideband reconfigurable leaky wave X-band antenna,” *IEEE Access*, vol. 7, pp. 127320–127326, 2019, doi: 10.1109/ACCESS.2019.2939097. [108] Y. Yashchyshyn *et al.*, “28 GHz Switched-Beam Antenna Based on S-PIN Diodes for 5G Mobile Communications,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 2, pp. 225–228, Feb. 2018, doi: 10.1109/LAWP.2017.2781262. [109] N. Javanbakht, B. Syrett, R. E. Amaya, and J. Shaker, “A Review of Reconfigurable Leaky-Wave Antennas,” *IEEE Access*, vol. 9. Institute of Electrical and Electronics Engineers Inc., pp. 94224–94238, 2021. doi: 10.1109/ACCESS.2021.3093775. [110] D. G. Chen and K. W. Eccleston, “Substrate integrated waveguide with corrugated wall,” in *Proceedings of 2008 Asia Pacific Microwave Conference, APMC 2008*, 2008. doi: 10.1109/APMC.2008.4958218. [111] K. W. Eccleston, “Mode analysis of the corrugated substrate integrated waveguide,” *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 10, pp. 3004–3012, 2012, doi: 10.1109/TMTT.2012.2209453. [112] A. Bansal, C. J. Panagamuwa, and W. G. Whittow, “Conformal Millimeter-Wave Corrugated Substrate Integrated Waveguide Slot Array Antenna,” *2023 8th Int. Conf. Smart Sustain. Technol.*, pp. 1–4, Jun. 2023, doi: 10.23919/SPLITECH58164.2023.10193713. [113] Y. Lin, Y. Zhang, H. Liu, Y. Zhang, E. Forsberg, and S. He, “A Simple High-Gain Millimeter-Wave Leaky-Wave Slot Antenna Based on a Bent Corrugated SIW,” *IEEE Access*, vol. 8, pp. 91999–92006, 2020, doi: 10.1109/ACCESS.2020.2993999. [114] D. Cho and H. Y. Lee, “Folded corrugated SIW (FCSIW) slot antenna for backlobe suppression,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 12, pp. 1276–1279, 2013, doi: 10.1109/LAWP.2013.2283535. [115] K. W. Eccleston, “Half-mode corrugated substrate integrated waveguide mode behavior,” in *2013 IEEE International Wireless Symposium, IWS 2013*, 2013. doi: 10.1109/IEEE-IWS.2013.6616708. [116] U. Pandey, P. Singh, N. P. Gupta, R. Singh, and A. Bansal, “Wideband leaky-wave antenna with dumbbell-shaped slots on substrate integrated waveguides with twisted corrugations,” *Electron. Lett.*, vol. 59, no. 20, pp. 3–5, 2023, doi: 10.1049/ell2.12991. [117] A. Bansal and W. G. Whittow, “Leaky Wave Antenna on a Half-Mode Integrated Digitated Capacitor-based Corrugated Substrate Integrated Waveguide with Tilted Vertical Slots,” in *2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, IEEE, 2023, pp. 1–4. doi: 10.1109/MAPCON58678.2023.10464096. [118] A. Lai, T. Itoh, and C. Caloz, “Composite Right/Left-Handed Transmission Line Metamaterials,” *IEEE Microwave Magazine*, pp. 34–50, 2004. [119] A. A. Houck, J. B. Brock, and I. L. Chuang, “Experimental Observations of a Left-Handed Material That Obeys Snell’s Law,” *Phys. Rev. Lett.*, vol. 90, no. 13, p. 4, 2003, doi: 10.1103/PhysRevLett.90.137401. [120] A. Dadgarpour, B. Zarghooni, B. S. Virdee, and T. A. Denidni, “Beam tilting antenna using integrated metamaterial loading,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2874–2879, 2014, doi: 10.1109/TAP.2014.2308516. [121] A. Dadgarpour, B. Zarghooni, B. S. Virdee, and T. A. Denidni, “One- and

Two-Dimensional Beam-Switching Antenna for Millimeter-Wave MIMO Applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 564–573, Feb. 2016, doi: 10.1109/TAP.2015.2508478. [122] S. S. Bukhari, J. Vardaxoglou, and W. Whittow, "A metasurfaces review: Definitions and applications," *Appl. Sci.*, vol. 9, no. 13, 2019, doi: 10.3390/app9132727. [123] L. Boccia, I. Russo, G. Amendola, and G. Di Massa, "Tunable frequency-selective surfaces for beam-steering applications," *Electron. Lett.*, vol. 45, no. 24, pp. 1213–1215, 2009, doi: 10.1049/el.2009.2577. [124] S. Narayan and R. M. Jha, "Electromagnetic Techniques and Design Strategies for FSS Structure Applications [Antenna Applications Corner]," *IEEE Antennas Propag. Mag.*, vol. 57, no. 5, pp. 135–158, Oct. 2015, doi: 10.1109/MAP.2015.2474867. [125] A. Kesavan, M. Mantash, and T. A. Denidni, "Beam-switching millimetre-wave antenna using cantilever-based FSSs," *IET Microwaves, Antennas Propag.*, vol. 12, no. 13, pp. 2019–2024, Oct. 2018, doi: 10.1049/iet-map.2018.5017. [126] A. Kesavan, M. Mantash, J. Zaid, and T. A. Denidni, "A dual-plane beam-sweeping millimeter-wave antenna using reconfigurable frequency selective surfaces," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 10, pp. 1832–1836, Oct. 2018, doi: 10.1109/LAWP.2018.2867331. [127] L. Y. Ji, Z. Y. Zhang, and N. W. Liu, "A Two-Dimensional Beam-Steering Partially Reflective Surface (PRS) Antenna Using a Reconfigurable FSS Structure," *IEEE Antennas Wirel. Propag. Lett.*, vol. 18, no. 6, pp. 1076–1080, Jun. 2019, doi: 10.1109/LAWP.2019.2907641. [128] W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo, "A beam steering horn antenna using active frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6218–6223, 2013, doi: 10.1109/TAP.2013.2280592. [129] J. R. Reis *et al.*, "FSS-Inspired Transmitarray for Two-Dimensional Antenna Beamsteering," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2197–2206, 2016, doi: 10.1109/TAP.2016.2543802. [130] G. H. Elzwawi, H. H. Elzwawi, M. M. Tahseen, and T. A. Denidni, "Frequency selective surface-based switched-beamforming antenna," *IEEE Access*, vol. 6, pp. 48042–48050, Jul. 2018, doi: 10.1109/ACCESS.2018.2850808. [131] C. Gu *et al.*, "Dual-band electronically beam-switched antenna using slot active frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1393–1398, Mar. 2017, doi: 10.1109/TAP.2016.2647578. [132] A. Goudarzi, M. M. Honari, and R. Mirzavand, "A Millimeter-Wave Fabry-Perot Cavity Antenna with Unidirectional Beam Scanning Capability for 5G Applications," *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 1787–1796, 2022, doi: 10.1109/TAP.2021.3118796. [133] A. Goudarzi, M. M. Honari, and R. Mirzavand, "A High-Gain Leaky-Wave Antenna Using Resonant Cavity Structure with Unidirectional Frequency Scanning Capability for 5G Applications," *IEEE Access*, vol. 9, pp. 138858–138865, 2021, doi: 10.1109/ACCESS.2021.3118286. [134] S. Zahra *et al.*, "Electromagnetic Metasurfaces and Reconfigurable Metasurfaces: A Review," *Front. Phys.*, vol. 8, pp. 1–16, Jan. 2021, doi: 10.3389/fphy.2020.593411. [135] T. Li and Z. N. Chen, "Control of Beam Direction for Substrate-Integrated Waveguide Slot Array Antenna Using Metasurface," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2862–2869, Jun. 2018, doi: 10.1109/TAP.2018.2823755. [136] Y. Yin *et al.*, "Design of a 2-bit Dual-Polarized Reconfigurable Reflectarray With High Aperture Efficiency," *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 542–552, Jan. 2024, doi: 10.1109/TAP.2023.3326951. [137] M. Bodehou, E. Martini, S. Maci, I. Huynen, and C. Craeye, "Multibeam and Beam Scanning with Modulated Metasurfaces," *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1273–1281, 2020, doi: 10.1109/TAP.2019.2944554. [138] J. B. Gros, V. Popov, M. A. Odit, V. Lenets, and G. Lerosey, "A Reconfigurable Intelligent Surface at mmWave Based on a Binary Phase Tunable Metasurface," *IEEE Open J. Commun. Soc.*, vol. 2, no. April, pp. 1055–1064, 2021, doi: 10.1109/OJCOMS.2021.3076271. [139] Y. Zhang, Z. Han, S. Tang, S. Shen, C.-Y. Chiu, and R. Murch, "A Highly Pattern-Reconfigurable Planar Antenna With 360deg Single- and Multi-Beam Steering," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6490–6504, 2022. [140] X. Wan *et al.*, "Reconfigurable Sum and Difference Beams Based on a Binary Programmable Metasurface," *IEEE Antennas Wirel. Propag. Lett.*, vol. 20, no. 3, pp. 381–385, 2021, doi: 10.1109/LAWP.2021.3050808. [141] A. Araghi *et al.*, "Reconfigurable Intelligent Surface (RIS) in the Sub-6 GHz Band: Design, Implementation, and Real-World Demonstration," *IEEE Access*, vol. 10, pp. 2646–2655, 2022, doi: 10.1109/ACCESS.2022.3140278. [142] B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, and D. F. Sievenpiper, "Scalar and tensor holographic artificial impedance surfaces," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3212–3221, 2010, doi: 10.1109/TAP.2010.2055812. [143] B. Rana, S. S. Cho, and I. P. Hong, "Review Paper on Hardware of Reconfigurable Intelligent Surfaces," *IEEE Access*, vol. 11, no. February, pp. 29614–29634, 2023, doi: 10.1109/ACCESS.2023.3261547. [144] J. Rains *et al.*, "High-Resolution Programmable Scattering for Wireless Coverage Enhancement: An Indoor Field Trial Campaign," *IEEE Trans. Antennas Propag.*, vol. 71, no. 1, pp. 518–530, 2023, doi: 10.1109/TAP.2022.3216555. [145] A. Araghi, M. Khalily, P. Xiao, F. Wang, and R. Tafazolli, "Systematic Design of a Holographic-Based Metasurface Reflector in the Sub-6 GHz Band," *IEEE Antennas Wirel. Propag. Lett.*, vol. 21, no. 10, pp. 1960–1964, 2022, doi: 10.1109/LAWP.2022.3186922. [146] A. Bansal and W. Whittow, "Figuring out Impaired Reconfigurable Intelligent Surfaces," *TechRxiv Prepr.*, 2024, doi: 10.36227/techrxiv.171051649.95959056/v1. [147] A. Araghi, M. Khalily, P. Xiao, and R. Tafazolli, "Holographic-Based Leaky-Wave Structures: Transformation of Guided Waves to Leaky Waves," *IEEE Microw. Mag.*, vol. 22, no. 6, pp. 49–63, 2021, doi: 10.1109/MMM.2021.3064118. [148] Y. Wang, Q. Feng, X. Kong, H. Liu, J. Han, and L. Li, "Multi-Feed Beam-Switchable Cylindrical Conformal Holographic Metasurface Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 23, no. 3, pp. 970–974, 2023, doi: 10.1109/LAWP.2023.3340682. [149] D. Kampouridou and A. Feresidis, "Tunable Multibeam Holographic Metasurface Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 21, no. 11, pp. 2264–2267, 2022, doi: 10.1109/LAWP.2022.3192977.