Direct Optimisation of a Five-State Reconfigurable Reflectarray for 5G Applications

Mustafa Murat Bilgic, Min Zhou
TICRA, Copenhagen, Denmark, {mmb,mz}@ticra.com

***Abstract*—This paper presents the preliminary design of reconfigurable reflectarrays using a direct optimisation approach, which has not been done before. The reflectarray employs a five-state configuration based on an aperture-coupled stacked patch element, offering phase quantisation within a 320° dynamic range. It operates in the 24.5-27.5 GHz band and is tailored for 5G applications. Several reflectarrays have been optimised to achieve beam scanning over ±70° with strict side lobe suppression. Furthermore, reflectarrays that radiate a fan-shaped beam have been optimised. The study confirms the suitability of this array element for beam-steering and shaped beam reflectarrays and highlights the simplicity of using the direct optimisation approach in antenna design.**

***Index Terms*—Reconfigurable reflectarrays, 5G, optimisation**

I. Introduction

In the last decade, research, and development of transmit- and reflectarrays have gained momentum and many advanced reflectarray antennas (RAs) have been designed [1]. The latest research has shown that reflectarrays can be used to provide solutions which are not possible using conventional technologies.

One of the emerging areas where reflectarray antennas can provide affordable and efficient solutions is applications that require beam collimation and adaptive pattern scanning. With the application of 5G technology, it has been found that traditional means of adapting to the wireless propagation environment, such as enhancing the capabilities of base stations and terminals, and optimising the networking structure, are all ineffective due to the easily blocked characteristics of millimeter waves [2]. Recently, there is a lot of work published in the literature where reconfigurable intelligent surfaces (RIS) and reconfigurable reflectarray antennas (RRA) are demonstrated to overcome the aforementioned issues with communication channels. Extensive comparative studies and definitions regarding RISs and RRAs, and their applications can be found in [2]–[4]. It is a broad consensus of the academia and industry that RISs and RRAs can revolutionise the current communication paradigm of adapting to channels using modulation and coding techniques to artificially configure channels for optimised performance [4].

By changing the reflection phase of each unit cell in a reflectarray it is possible to collimate or shape the antenna far-field pattern to a desired specification. An arbitrary phase shift between 0° and 360° will help achieve perfect phase correction hence full control on optimising the beam shape. For pattern scanning, ideally, it would be desired to have the same arbitrary phase shift to actively steer the beam in the desired direction. However, a reconfigurable reflectarray with continuous 0°-360° phase range controlled unit cells is technically and practically very challenging. To overcome bandwidth, linearity and complexity issues of beam-steerable reflectarrays, discreate phase quantisation schemes have been adopted. In [5], [6], a general overview of the existing designs that have implemented 1-bit, 2-bit and 3-bit quantisation schemes have been discussed with comparisons from the literature and how they also can be applied for polarisation conversions. A wide range of research is focused on phase quantisation and the work in the literature shows that a good beam-steering in a wide band and range can be achieved, some examples of these works can be found in [7], [8] and [9].

The conventional method for designing discrete reconfigurable reflectarrays is to employ the phase-only optimisation approach, as described in [1]. This approach involves first determining the necessary phase and subsequently calculating the individual mode for each array element. However, due to its two-step nature, it lacks complete control over the far-field pattern. This limitation makes it challenging to design reflectarrays with intricate beam shapes, such as shaped beams or pencil beams with stringent side lobe suppression requirements. In contrast, by adopting a direct optimisation approach, as described in [10], where the individual modes for all array elements are optimised simultaneously based on the desired far-field pattern, it becomes easier to precisely control the shape of the far-field pattern and achieve complex beam shapes. This paper aims to illustrate the application of the direct optimisation approach in the design of discrete reconfigurable reflectarrays.

To accomplish this, we employed the commercial software tool QUPES [11], which is specifically tailored for the design and analysis of quasi-periodic surfaces, including reflectarrays. QUPES adopts a direct optimisation approach, as elaborated in [10], for reflectarray design. This paper presents an initial design of an array element intended for operation within the 24.5-27.5 GHz frequency band, utilising a five-step phase quantisation scheme achieved through the incorporation of an SP4T switch. We chose the 24.5-27.5 GHz band for this design, as it is one of the millimeter-wave frequency bands earmarked for 5G communication systems.

II. Element Design

Aperture-coupled stacked patch antennas are well known for their high gain and wide bandwidth properties [12]. In

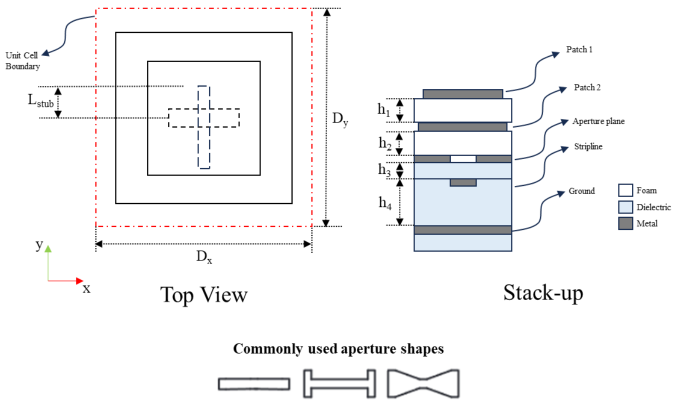


Fig. 1. Aperture coupled stacked patch element.

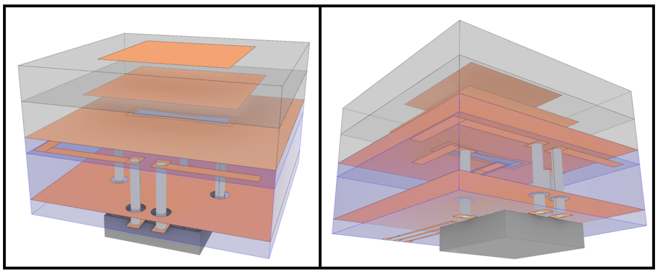


Fig. 2. Proposed reconfigurable array element geometry.

this work, we consider an array element based on aperture coupled stacked patch antenna topology. Fig. 1 shows the aperture coupled stacked patch setup with some of the widely used aperture shapes. By varying the stub length (L_{stub}), it is possible to achieve a wide reflection phase variation angle control.

The proposed array element geometry is shown in Fig. 2. The array element has a stackup of five layers. The SP4T switch is placed below the ground plane at the very bottom. The switch inputs and outputs are connected to phase quantisation striplines in the mid copper layer by vias. Confining main RF paths in the mid-layer gives us the ability to reduce reflection losses and isolate the RF layer from the DC circuitry and the discrete circuit components required to operate the switch, which can degrade performance due coupling. The SP4T switch intended to be implemented in the PUC operated by connecting the input to one of the four outputs using two control bits. A single bit is used to enable and disable the switch device. The two control bits together with the enable/disable bit creates five possible phase modes.

For demonstration purposes for the paper, where we consider a preliminary design, the array element has been simplified as shown in Fig. 3. The model has been built using QUPES. The switch is not included in the model, but the switching function is implemented in the mid layer. The five possible switching states of the mid layer are shown in Fig. 4. Circuitry for biasing and controlling the switch is out of the scope of this preliminary study.

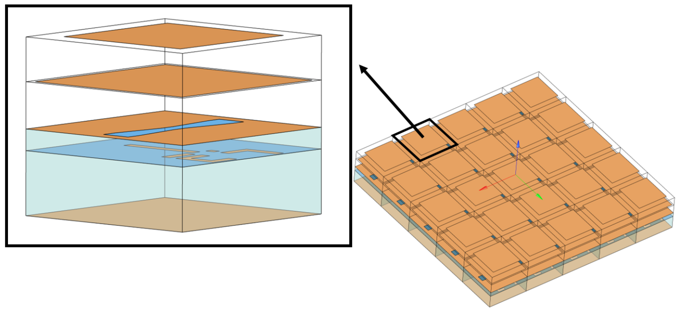


Fig. 3. Simulation model of preliminary reconfigurable array element.

The design has been optimised to have a linear phase variation and low reflection loss. Fig. 5 shows the reflection magnitude and phase vs. frequency plots for the optimised array element. These results show that the proposed structure is a promising candidate as array element for a reconfigurable reflectarray. It can be seen from Fig. 5. that the phase variation is almost linear throughout the 24.5-27.5 GHz band. At each frequency, the five modes can provide a phase quantisation in the dynamic range of 320° and the peak reflection loss is below 0.6 dB for all modes. A scattering matrix database for the five discrete modes at five frequencies has been calculated and will later be used for fast optimisation of reflectarrays.

III. Reflectarray Design

This section presents an exemplification of the design process for a reconfigurable reflectarray, with a focus on a practical 5G application case depicted in Fig. 6. In this application scenario, the reflectarray shall redirect incoming waves originating from a telecommunications source. These incoming waves may be obstructed by obstacles, e.g., by a wall, and the reflectarray is utilised to steer the incoming wave towards the intended reception area. With this objective in

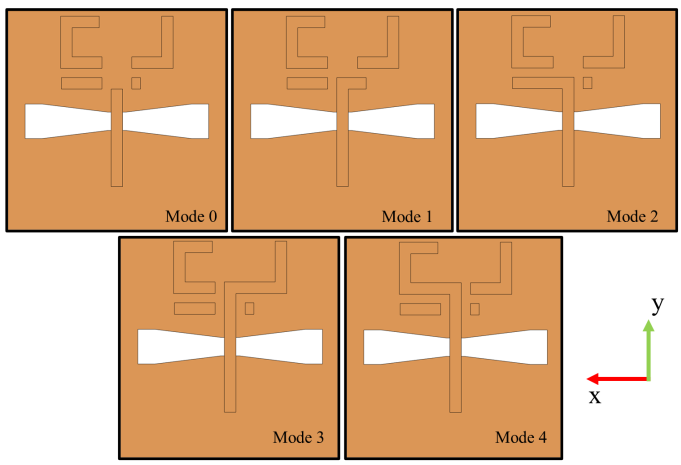
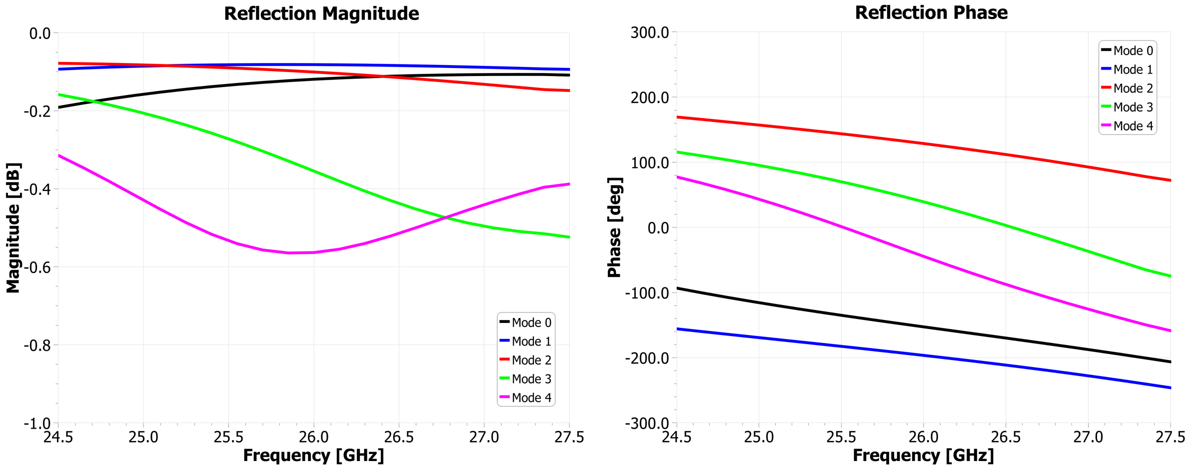


Fig. 4. The five discrete operation modes of the array element. The view is from below the aperture slot.



(a) (b)

Fig. 5. Reflection coefficients of the simulation model of the array element, (a) reflection magnitude and (b) reflection phase.

mind, the redirected beam may take the form of a wider beam, such as a fan-shaped beam, or it may consist of scanned pencil beams directed in various directions. In our investigation, we will focus on both scenarios. For the scanned pencil beam, we aim to design the reflectarray to perform beam scanning over a considerable range. Furthermore, we introduce an additional level of complexity to the beam pattern by imposing stringent side lobe suppression requirements on the scanned beams. For the fan-shaped beam, we design the reflectarray to radiate fan-shaped beams with different beam width.

All the simulations presented in this paper were carried out on an Intel(R) Core(TM) i9-12900F 2.4 GHz computer

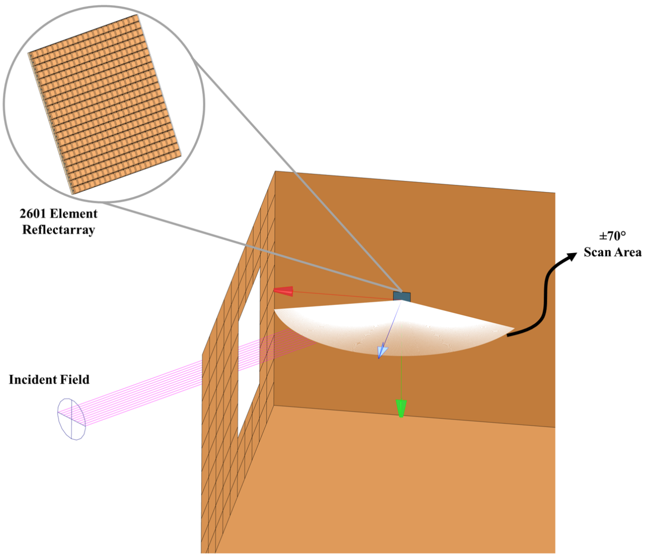


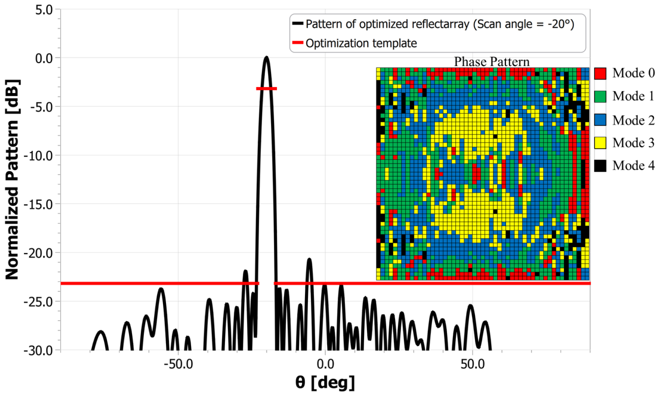
Fig. 6. Application case where the reflectarray redirects the incoming plane wave (incidence angle of the plane wave is at $\theta = 20°$) to the intended reception area.

A. *Scanned Beams*

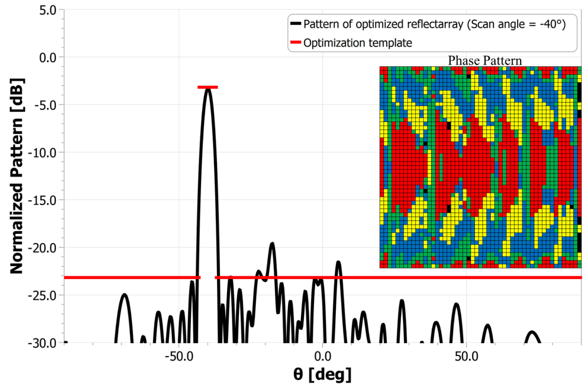
The reflectarray has a dimension of $25{\times}25\,\mathrm{cm}^2$ and is illuminated by a plane wave source symbolising a source as a base station stationed far away. There are 2601 array elements in the reflectarray, and the entire antenna is modelled using QUPES. The optimisation variables are the discrete modes of the array elements, resulting in a total of 2601 optimisation variables. As optimisation goal, the reflectarray is optimised to redirect the peak for each scan angle individually. Furthermore, a side lobe suppression has been enforced to be 25 dB below peak.

In Fig. 7a, the radiation pattern of the reflectarray, which has been optimised for redirecting the incident plane wave to $\theta = -20°$ (the specular direction), is presented. The discrete modes of each individual array element, along with the optimisation template marked by red lines, are visible in this figure. The optimisations shown in this work are done for a single frequency which is selected to be 26 GHz. Similar optimisations can be performed to calculate the switch states for all intermediary frequency bands and pointing angles to create a lookup table for controlling and steering the beam. In a conventional reflectarray designed to redirect a plane wave to the specular direction, the phase variation across the reflectarray surface remains constant. However, in our case, all five modes are utilised in a somewhat irregular fashion. This is a direct consequence of the imposed side lobe suppression requirements. The result shows that we achieve a directive beam directed towards $\theta = -20°$, with side lobes measuring more than 20 dB below the peak value.

Similarly, the radiation pattern of the reflectarray optimised to scan towards $\theta = -40°$ is shown in Fig. 7b. Again, we have a directive beam towards $\theta = -40°$ with side lobes around 20 dB below peak. The distribution over the reflectarray surface show the phase progression to scan the beam away from the specular direction, but there are clearly irregular distortions due to the side lobe suppressions.



(a)



(b)

Fig. 7. Far-field radiation pattern of the optimised reflectarray for (a), $\theta = -20^\circ$ and (b) $\theta = -40^\circ$. The color codes for the five operating modes over the reflectarray surface is shown together with the radiation pattern. (Optimized for 26 GHz)

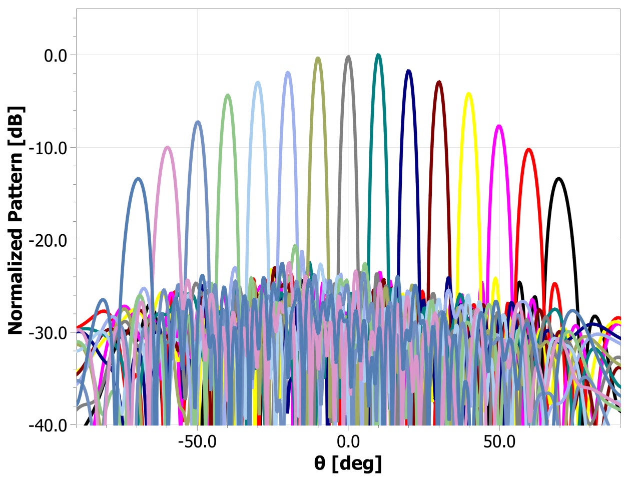


Fig. 8. Far-field radiation pattern of the optimised reflectarrays for scanned beams between $\theta = \pm 70^\circ$.(All beams have been optimized for 26 GHz)

Remarkably, as evident from Fig. 7, it is apparent that mode 4 is sparingly employed, suggesting that a conventional 2-bit design would be adequate for achieving the beam scanning requirements addressed in this study.

In Fig. 8, we show far-field radiation pattern of all the optimised reflectarrays for scanned beam between $\theta = \pm 70^\circ$. It is seen that it is indeed possible to scan within this range, albeit significant scan loss at the higher scanning angles, as expected.

The time to complete one optimisation for a certain scan angle requires only approximately two minutes, meaning that the design of all the 15 beams took half a hour. For more information about the design approach, the reader is referred to [10].

B. Fan-shaped Beams

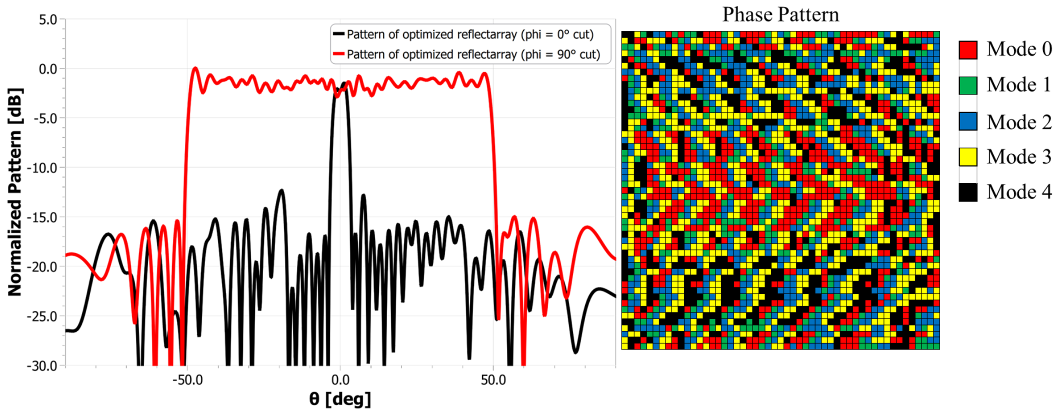
In addition to scanned beams, other pattern shapes can be achieved, depending on the intended reception area. In this section, we show the results for fan-shaped beam designs. The design process is identical to that of the scanned beams, but as optimisation goal, the reflectarray is optimised to reshape the incidence field into a fan shape, i.e, wide beam in one plane and a narrower beam in the orthogonal plane. Two designs are considered, one with a beamwidth for $\theta = \pm 50^\circ$ and another for $\theta = \pm 20^\circ$.

Fig. 9 shows the radiation pattern of the two optimised designs, together with color codes of the discrete modes of each individual array element over the reflectarray surface. It is seen here that the reflectarray radiates in Fig. 9a a wide beam between $\theta = \pm 50^\circ$ and in Fig. 9b a slightly narrower beam between $\theta = \pm 20^\circ$. Obviously, there are some ripples in the beam pattern, but this is expected since the reflectarray only operate with 5 modes. Contrary to the pencil beam cases, it is seen in the color codes that mode 4 is employed to a larger extent, indicating that additional bits are required if one is interested in reducing the ripples in the pattern.

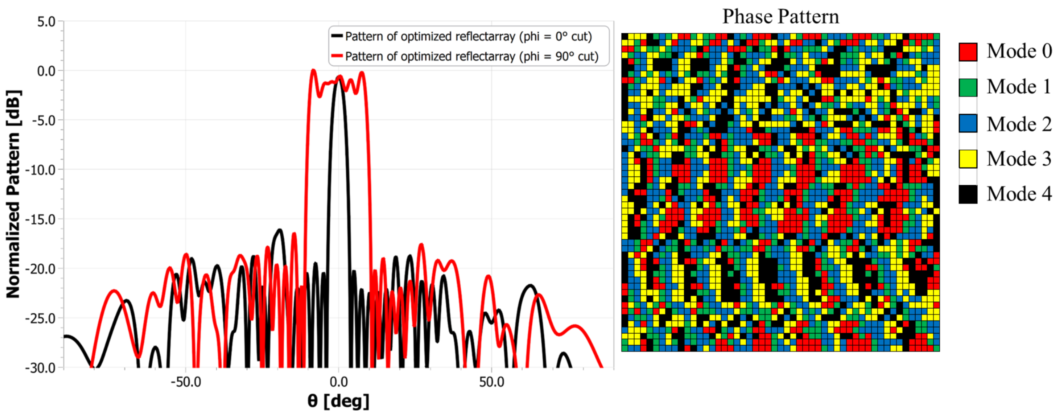
Similar to before, the optimisation takes approximately two minutes. This also clearly demonstrate the advantages of using QUPES compared to other commercial general purpose softwares as the design of such shaped beams are not straight forward using these softwares.

IV. Conclusions

This paper presents the design of reconfigurable reflectarrays employing a five-state configuration, using a direct optimisation approach. The array element is based on an aperture-coupled stacked patch element that can be configured to operate in five distinct modes, providing a phase quantisation capability spanning a dynamic range of 320°, while operating within the 24.5-27.5 GHz frequency band. The work done is within the context of a 5G application, where the reflectarray is to facilitate beam scanning over an angular range of $\pm 70^\circ$, all while subject to stringent side lobe suppression requirements. Similarly, it has been shown that with a 5-state phase discretisation, it is also possible to realise reflectarrays to



(a)



(b)

Fig. 9. Far-field radiation pattern of the optimised reflectarray for (a), $\theta = \pm 50°$ fan beam and (b) $\theta = \pm 10°$ fan beam. The color codes for the five operating modes over the reflectarray surface is shown together with the radiation pattern. (Optimized for 26 GHz)

radiate fan-shaped beam patterns through direct optimisation, which can be used again for scanning and wide beam coverage. The outcomes of this investigation show the suitability of the selected array element for applications involving beam-steering reconfigurable reflectarrays. Additionally, the study demonstrates the ease of utilising the direct optimisation approach in the design of such antennas.

References

[1] J. Huang and J. A. Encinar, *Reflectarray Antennas*. IEEE Press, 2008.

[2] X. Zou, J. Yao, K. L. Chung, G. Lai, W. Zeng, and W. Gu, "A comparative study between reconfigurable intelligent surface and reflectarray antenna," in *Proc. 5th ICEICT*, 2022.

[3] Z. Fu, X. Zou, Y. Liao, G. Lai, Y. Li, and K. L. Chung, "A brief review and comparison between transmitarray antennas, reflectarray antennas and reconfigurable intelligent surfaces," in *Proc. 3rd TOCS*, 2022.

[4] L. Chen, K. L. Chung, G. Lai, J. Yao, X. Zou, X. Cheng, K. Zheng, and Y. Li, "Cross deployment of active and passive reconfigurable intelligent surfaces (riss) for next-generation communications," in *Proc. 5th ICEICT*, 2022.

[5] H. Luyen, J. H. Booske, and N. Behdad, "2-bit phase quantization using mixed polarization-rotation/non-polarization-rotation reflection modes for beam-steerable reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 68, no. 12, 2020.

[6] H. Yu, Z. Zhang, J. Su, M. Qu, Z. Li, S. Xu, and F. Yang, "Quad-polarization reconfigurable reflectarray with independent beam-scanning and polarization switching capabilities," *IEEE Trans. Antennas Propag.*, vol. 71, no. 9, pp. 7285–7298, 2023.

[7] C. C. Cheng and A. Abbaspour-Tamijani, "Design and experimental verification of steerable reflect-arrays based on two-bit antenna filterantenna elements," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1181–1184, 2009.

[8] R. Sorrentino, "Mems-based reconfigurable reflectarrays," *Proc. 2nd Eur. Conf. Antennas Propag. (EuCAP), Edinburgh*, pp. 1–7, 2007.

[9] B. Xi, Y. Xiao, K. Zhu, Y. Liu, H. Sun, and Z. Chen, "1-bit wideband reconfigurable reflectarray design in ku-band," *IEEE Access*, vol. 10, pp. 4340–4348, 2022.

[10] M. Zhou, S. B. Sørensen, O. S. Kim, E. Jørgensen, P. Meincke, and O. Breinbjerg, "Direct optimization of printed reflectarrays for contoured beam satellite antenna applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1995–2004, 2013.

[11] "QUPES Software," TICRA, Denmark.

[12] M. M. Bilgic and K. Yegin, "High gain, wideband aperture coupled microstrip antenna design based on gain-bandwidth product analysis," *Appl. Comput. Electromagn. Soc. J. (ACES)*, vol. 29, no. 8, 2014.