Dual-Band Shared-Aperture Multiple Antenna System with Beam Steering for 5G Applications

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Published in: I E E E Transactions on Circuits and Systems. Part 2: Express Briefs

DOI (link to publication from Publisher): https://doi.org/10.1109/TCSII.2022.3201009

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Publication date: 2022

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):

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Dual-Band Shared-Aperture Multiple Antenna System with Beam Steering for 5G Applications

Guangwei YANG, Member, IEEE, and Shuai ZHANG, Senior Member, IEEE

Abstract—This brief presents a high-efficiency shared-aperture multiple antenna system. Unlike general shared-aperture antennas, the proposed antenna system with the size of 0.384×0.384×0.171λ3 makes high reuse the aperture in the two respective frequency bands, and the antenna structures of the two bands can each generate positive mutual enhancement for their radiating characteristics in the two bands. The flat Luneburg lens can realize beam steering capability for mm-wave antenna from 25.5 to 29.5 GHz with the gain of 19.3 dBi and improve the wide-angle scanning matching impedance for the Sub-6 GHz antenna from 3.2 to 3.45 GHz with the gain of 6.2 dBi. Meanwhile, as the radiating patch of the Sub-6 GHz antenna, the meta-surface can reduce the focal distance of the lens and maintain the high gain of the mm-wave antenna. Hence, a compact antenna system can achieve beam steering capabilities (up to 112°) in the Sub-6 GHz band and (up to 56°) mm-wave band with high gain, respectively. And the port isolation of the proposed antenna system between two frequency bands is generally better than 25 dB and even up to 40 dB at the Sub-6 GHz band. As reported in the simulated and measured results in a linear array, the antenna system shows good radiating performance with a dual-polarization state. Hence, the proposed multiple antenna system is a good candidate for 5G applications because of the high-efficiency, beam steering with high gain and full 5G band.

Index Terms—Sub-6 GHz, multiple antenna system, millimeter-wave (mm-wave), dual-band, beam steering, large frequency ratio.

I. INTRODUCTION

In the last decade, with the development of wireless communication technologies such as the internet of things (IoT) and intelligent transportation systems (ITS), the multiple antenna system has received more attention and widely applied because of its capabilities such as enhancing the reliability, improving the channel capacity, etc. In addition, in the face of complex communication environments such as ultradense networks, moving networks, and so on [1]-[4], the new 5G technologies covering the full frequency bands (Sub-6 GHz and mm-wave band) should be explored. From the above standpoints, a smart multiple antenna system is proposed to be applied to the wireless base station as shown in Fig. 1. This antenna system can work in both the Sub-6 GHz band and mm-wave bands, so that the bands can be switched according to the application scenario, such as urban areas for dense, airports for specific targeted spots, and rural and suburban areas for large coverage, which can avoid the disadvantages of limited capacity in the low-frequency band and limited transmission distance in the high-frequency band [5].

Shared-aperture technology as a dual-band or even multi-band antenna technology has been widely applied in 5G wireless communication systems, primarily focused on the following aspects: a) the antenna radiating structures of different frequency bands are staggered together or interlaced in a co-aperture form. For this shared-aperture antenna, it is easy to design, but has a lower aperture reuse efficiency [6] and tends to disturb each other's radiating performance. b) The antenna radiating structures are overlapped with each other, and some technologies such as meta-surface are applied into the antenna to ensure a radiating performance, which has high aperture reuse efficiency [7]-[11]. c) The aperture of this antenna is still overlapped, which not only has a high aperture reuse efficiency, but also has a positive mutual enhancement effect to each other in the respective bands [12]. Based on the above

This work was supported by the UK Royal Society Newton International Fellowship under Grant NIF/R1/191365. (Corresponding author: Guangwei Yang)

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shared-aperture technology, some shared-aperture dual-band antennas for Sub-6 GHz and mm-wave are presented in the Table I. However, most shared-aperture antennas with both Sub-6 GHz and mm-wave bands could only realize high aperture reuse efficiency, high gain, but rarely have the same functionality as the above aspect (c). Additionally, MIMO technology has been widely applied in 5G communication because of its higher data rate, reduction in bit error rate (BER), wide coverage, high isolation [13][14]. Therefore, for designing the shared-aperture antenna with a large frequency ratio in Sub-6GHz and mm-wave bands, we not only achieve the above-mentioned antenna performance, but also focus on dual polarization, beam steering, array characteristics, etc. In this brief, a new shared-aperture multiple antenna system is presented, which allows for high reusability of the aperture in the two respective frequency bands. Meanwhile, the designing structure can have a positive mutual enhancement effect on the radiating characteristics in two bands. The measurements and simulations based on the analysis of the proposed antenna system are available to demonstrate the above characteristics. Noted that the beam steering capability in the low-frequency band is improved, which can be realized in the coverage of ±56° with a low gain reduction, and the antenna with the beam steering capability in the mm-wave band is also realized. Hence, a smart antenna system can achieve the beam steering capability in the Sub-6 GHz band and mm-wave band.

II. GUIDELINES FOR ANTENNA DESIGN AND ANALYSIS

A. Design mechanism

As described above, for an excellent shared-aperture antenna system, it not only has a high aperture reuse efficiency, but its design also has a positive effect on each other’s radiating characteristics in the respective bands. Facing the complex communication environments and high path loss, the mm-wave antenna needs higher gain and flexible beam-steering capability. And the Sub-6 GHz antenna should have a compact structure for arranging into MIMO arrays for beamforming capability. Hence, the proposed design principle of the antenna is shown in Fig. 2. For the mm-wave band, a dual-polarization patch antenna is designed to combine a transmitted flat Luneburg lens for the high gain and beam steering capability. The patch antenna based on the meta-surface structure is designed and embedded between the lens and mm-wave antenna for Sub-6 GHz communication systems. The high aperture reuse efficiency is realized by the proposed design. More importantly, the meta-surface is applied to reduce the focal distance of the lens and improve the gain of the mm-wave antenna. Additionally, for the Sub-6 GHz band, the lens could improve the wide-angle scanning impedance of the array. A detailed description of the principles will be covered below.

B. Flat Luneburg lens

As shown in Fig. 2, the flat Luneburg lens (all-dielectric flat lens) can be designed based on the transmitted optics and Maxwell’s equations [15]-[17]. The permittivity of the flat lens is obtained as follow [18]

$$\varepsilon_r = \frac{2 - \frac{R^2 - x'^2 + (\delta x')^2}{(2R)^2}}{\frac{1}{\delta^2}}$$

(1)

Where R it the radius of the lens, $x'$ and $z'$ are the value of the flat lens in the X and Z-direction, respectively. $x'$ and $z'$ can be obtained as follow:

$$z' = \frac{q}{\sqrt{R^2 - x'^2}} \quad x' = x$$

(2)

We can get the distribution of the dielectric constant of the transformed flat lens is a continuous variable, for the sake of lens fabrication simplicity and reducing the loss of the substrate [19] based on Eq. (3), we will discrete the dielectric constant as shown in Table II.

$$\varepsilon_i = \sqrt{\varepsilon_{i-1} \varepsilon_{i+1}}$$

(3)

<table>
<thead>
<tr>
<th>Cyk</th>
<th>Hz</th>
<th>Rx</th>
<th>$\varepsilon_r$</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>6</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>b</td>
<td>5</td>
<td>15</td>
<td>8.6</td>
</tr>
<tr>
<td>c</td>
<td>4</td>
<td>12</td>
<td>6.1</td>
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<tr>
<td>d</td>
<td>3</td>
<td>9</td>
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<tr>
<td>e</td>
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<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>f</td>
<td>1</td>
<td>3</td>
<td>2.2</td>
</tr>
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</table>

C. Meta-surface design

To avoid the mm-wave reflection by the Sub-6 GHz patch, a new bandpass frequency selective surface (FSS) structure is designed. Based on the typical situation [20], the suggested design employs a cross-shaped slot structure that not only propagates the proposed mm-wave but also functions in the dual-polarization condition. However, the design performs poorly with a single layer structure, particularly at large angles of incidence. As a result, as illustrated in Fig. 3, a circular slot
is applied to solve this problem. For the proposed FSS, it can be treated as a parallel LC-circuit consisting of parallel lumped inductors and capacitors, which can be coupled to the magnetic and electric fields of the incident wave, respectively. Hence, a desired FSS structure is designed as follows: the approximate values of the capacitance and inductance are obtained by the equations in [21].

In this way we will get the rough value of the structure at the required frequency band, and then we optimize it with simulation software to finally get the parameter values. The specific parameter values shown in the following: \(d=0.2\)mm, \(g=4.2\)mm, \(s=1.9\)mm, and \(P=4.5\)mm. As shown in Fig. (b), the transmission coefficients of the proposed structure for different angles of incidence are given. Note that the transmitted loss at the operating frequencies of the proposed structure is very low and has slight effect with the angles of the incident wave. But the operating frequency band has a remarkable loss when the incidence angle is grown beyond 70°. Additionally, the phase of the incident wave has a slight variation with increasing the angle of the incident wave except for beyond 70°.

D. Feeding antennas

To design the proposed antenna system, it is necessary to design suitable low and high band antenna units to satisfy the 5G bands (FR1 and FR2) for both 3.4 and 28 GHz with the frequency ratio (up to 1:8). As shown in Fig. 4, the three-dimensional views of the proposed antenna units are given. Firstly, the Sub-6 GHz patch antenna unit is designed, which has a dual-polarized characteristic and comprises of two SMA connectors, a radiating patch (which is composed of the above FSS) on a thin substrate of Rogers RO4350B (the thickness of 0.762mm). The proposed antenna uses a basic coaxial feeding method, and an annular slot is used to improve the matching. For the mm-wave antenna unit, the microstrip patch consists of a square patch and four L-shaped strips, which are also printed on the thin substrate of Rogers RO4350B. This antenna unit also employs the coaxial feeding and is connected by the SMP connector. The L-shaped strip is used to optimize the radiating pattern, which can make the pattern radiate to the broadside direction and be symmetrical. All dimensions of the proposed antenna units, optimized by simulation, are shown in the following: \(L_s=27, K_s=4.5, H_0=10, L_p=2.5, L_h=4.8, g=1, H_p=0.762, K_p=0.6, H_1=7, D_3=18, H_3=3, D_4=24, H_3=4, D_5=30, H_5=5, D_6=36, H_6=6\). (unit: mm). In addition, these antennas have good radiating and impedance characteristics, and the bandwidth is narrow as the individual one.

E. The antenna system and performance improvement

As the proposed design concept, the proposed shared-aperture antenna system is designed as shown in Fig. 5. The mm-wave patch antenna with the flat Luneburg lens is shown in Fig. 5(a). And, in Fig. (b), the meta-surface-based Sub-6 GHz patch antenna and mm-wave patch antenna are combined. Then, these two antennas are combined as shown in Fig. 5(c) and (d), that is, the proposed shared-aperture dual-band antenna system. As we all know, although the spherical Luneburg lens is transformed into a flat Luneburg lens, the focal distance of the lens is unchanged. Generally, the focal distance of a Luneburg lens is the same as its radius, and the gain of the proposed lens will be affected when changing the focal distance. As shown in Fig. 5(a), the distance \((H_o)\) between the lens and the floor is changed, and the gain of the antenna will be varied as shown in Fig. 6. When \(H_o\) is greater than 18mm, the gain decreases. Meanwhile, the \(H_o\) is less than 18mm, the gain also drops and is up to 14.5 dBi at 28 GHz when it is 10mm. To be able to reduce the profile of the proposed antenna while maintaining its high gain performance, as shown in Fig. 5(c) and (d), a meta-surface structure is used to
achieve this performance. To explain the working mechanism of the meta-surface for the mm-wave antenna, the E-field distribution is given in Fig. 7. As shown in Fig. 7(a), when $H_0$ is 10mm, the feeding mm-wave antenna is not at the best focal position of the proposed lens. Hence, its spillover efficiency becomes poor. Note that the energy of the feeding antenna is radiated from both sides of the lens, and the plane wave after the lens transformation is not very well. In Fig. 7(b), the E-field distribution of the mm-wave antenna with the meta-surface is depicted to analyze the meta-surface’s effect on the mm-wave antenna. As described in Section II-C, the proposed meta-surface has good transformation characteristics, so that most of the electro-magnetic waves from the feeding source can be coupled and radiated into space by this structure. Therefore, the flat lens, the meta-surface and the mm-wave antenna are combined, and the E-field distribution is shown in Fig. 7(c). Note that the E-field from the feeding source is coupled as much as possible into the flat lens by the meta-surface, enhancing the spillover efficiency of the proposed lens so that it can radiate better plane waves. By compared with the E-field in Fig. 7(a), the improvement can be found to be significant. Additionally, when the feeding source is placed at the edges of the lens, the radiating characteristics are not as effective as the one at the center, but it also has high gain.

From the above analysis, the meta-surface is beneficial to enhancing the gain of the mm-wave antenna. Also, the flat lens has a positive effect on the radiating performance of the Sub-6 GHz antenna. Since the proposed flat lens is a pure dielectric structure, it can be used as a wide-angle impedance matching slab (WAIMS) for Sub-6 GHz antenna array [22]. As shown in Fig. 8, the periodic boundary is used to simulate the infinite array to verify the proposed performance. The patch antenna element is excited as the impedance network $Z_{mn}$, and the lens has an intrinsic impedance of $Z_{wm}$. In the infinite array, a series impedance networks are occurred, which can realize the impedance matching with the far-field space by the impedance of the lens. In Fig. 8(b), the active $|S_{11}|$ of the proposed and referenced antenna at 3.4 GHz with varying the scanning angles is presented to expound the work mechanism of the WAIMS (lens). Note that changing the distance between the WAIMS and the meta-surface antenna could affect the active $|S_{11}|$ of the proposed antenna obviously. Additionally, it is remarkable that the proposed lens could improve the wide-angle scanning impedance matching by compared with the reference antenna without the lens.

Based on the above design guideline, the proposed antenna system is fabricated and measured. As shown in Fig. 9, the simulated and measured radiating characteristics of the proposed shared-aperture antenna system are presented, which are in good agreement. For the Sub-6 GHz, the realized gain of the antenna is from 5.8 to 6.2 dBi in the operating frequency band from 3.2 to 3.45 GHz. The port isolation between both bands is better than 40 dB. For the mm-wave, the operating bandwidth is from 25.5 to 29.5 GHz and the port isolation between low and high frequency is better than 25 dB. The realized gain is up to 19.3 dBi in the frequency band. At the sideband, it is not very high due to the low transmittance of the meta-surface as shown in Fig. 3(b). Compared with referenced antennas, the radiating characteristics of the low frequency antenna has slightly variation, but which has a significant improvement in the mm-wave band. While reducing the lens height, the gain of the mm-wave antenna is significantly improved, by up to 5.3 dB compared to the reference antenna. Additionally, the reuse efficiency of the proposed shared-aperture antenna is up to 100%, more importantly, the aperture efficiency (Ae) at mm-wave band is up to 77.5%.

III. PERFORMANCE OF THE ARRAY

To validate the beam scanning performance of the proposed antenna system, one-by-four linear shared-aperture array is designed, fabricated, and tested in this section as shown in Fig. 10, which has the element-spacing of 36mm ($L_d$) for the low-frequency band. And five mm-wave antenna elements are arranged inside one of the low-frequency elements, where the element spacing is 5mm ($h_d$). The far field radiation performance in the low-frequency band is shown in Fig. 11. The main beam of the proposed array can scan from -56° to 56° and the gain of the array changes from 8.4 to 9.0 dBi, then decreases to 6.9 dBi with increasing the scanning angle. Within the proposed scanning range, the gain fluctuation of the array is less than 3 dB. To verify the improvement of the wide-angle scanning impedance matching by the flat lens, we also compare the two radiation patterns of the reference antenna without the flat lens (Ref.). Noted that the proposed design method can significantly improve the scanning beam, and the gain of this scanning pattern can be increased by 3.3 dB compared with the reference antenna. For the mm-wave band, as shown in Fig. 12, the scanning pattern of the proposed antenna at 28 GHz is drawn. It is observed that the beam can scan from around -28° to 28° with the realized gain varying from 19.31 to 16.4 dBi, which has a high gain with beam steering capability. More
Fig. 10. Shared-aperture antenna system prototype and measurements: (a) the structure; (b) measurement.

Fig. 11. Simulated and measured radiation patterns of the antenna at 3.4 GHz.

Fig. 12. Simulated and measured radiation patterns of the antenna at 28 GHz.

importantly, the pattern has a very low sidelobe level, whether it is scanning or not, especially its sidelobe level is less than -20 dB when it directs to broadside direction. In practice, the measured results of the pattern at 28 GHz are also described in this figure. By comparing with the simulations, note that the gain and scanning capability have been verified. The cross-polarization of the proposed antenna also low and lower than about -15 and -20 dB in two bands, respectively. And the maximum aperture efficiency of the antenna system is improved by 52.6%, up to 77.5% at 28 GHz.

V. Conclusion

This brief presents a high-efficiency shared-aperture dual-polarization antenna system with a large frequency ratio to apply for the 5G wireless communication system, which can realize the beam scanning in the range of ±56° with a low gain reduction at Sub-6 GHz from 3.2 to 3.45 GHz and reduce the profile of the lens with high gain to steer in the range of ±28° from 25.5 to 29.5 GHz. The gain of the antenna is up to 9.0 dBi at Sub-6G band, and 19.31 dBi at mm-wave band. The measurements and simulations of the proposed antenna system are presented as demonstrating the antenna system’s characteristics. Hence, a compact dual-band and dual-polarization shared-aperture multiple antenna system can realize the beam steering capability in the Sub-6 GHz band and mm-wave with high aperture reuse efficiency and aperture efficiency (77.5% at 28 GHz).

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