A Beam-Switching Antenna Array With Shaped Radiation Patterns

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***Abstract*—In this letter, a novel beam-switching array, which uses four patch elements to generate two anti-symmetric-shaped patterns, is proposed. Beam shaping is introduced into this design to realize a flat response in its two beams $\pm 45^\circ$ covering regions with less than ± 0.55 dB fluctuation. A synthesis process is derived in detail, and a prototype, including the array and a planar feeding structure, is built and tested. The measurement result agrees well with the simulated one, which verifies the validity of the synthesis algorithm.**

***Index Terms*—Beam shaping, beam-switching array, smart antenna.**

I. Introduction

SUFFERING in more and more noisy and crowded channel environments, wireless communication systems are resorting to newer resources beyond what time and frequency domain can provide. The smart antenna, as one kind of space-domain technique, has attracted more attention since it can exploit additional system capacity in a matured noise-constrained CDMA system, which has been widely applied in all 3G standards.

Basically, there are two approaches to implement this technique, namely, adaptive array and beam-switching array. The former is more sophisticated since it can realize dynamic beamforming in contrast to the latter's fixed beam scheme. However, this advantage is attained at the cost of complicated T/R modules and algorithm units as well as higher power consumption, which is not suitable in a limited source environment. Thus, beam switching is still competitive as only a small cost in system complexity is sacrificed to acquire a considerable improvement in performance [1].

Tracing the origin of beam-switching array, it is a technique evolved from the sector antenna, which uses shaped reflectors to restrict the beam into a desired angular region [2]. However, this kind of space splitting is not economical since each aperture is occupied by only one beam. To acquire higher aperture efficiency, Butler matrix- or Blass matrix-based switching arrays, whose beams can co-use one aperture, are proposed [3]–[6]. Nevertheless, this scheme is mainly aimed at providing enough space diversity with high gain in each beam to acquire better coverage. The beams are unshaped, and a blind area, whose gain drops dramatically from the peak region, exists between adjacent beams. Thus, the users may suffer from signal fading or even call drops when moving across this region [7]. Also, the variation in these blind areas increases the complexity in link budget estimation, which is undesirable in system design.

In this letter, a novel planar beam-switching array with shaped beams is proposed. Based on the Butler matrix aperture reuse idea, this design generates two 45° beams aiming at $\pm 22.5^\circ$ while sharing the same aperture. Four such arrays with a total of eight beams should be sufficient to provide 360° coverage. Unlike many traditional switching arrays, this design aims at providing a flat response in each beam rather than generating high-gain pencil beams, thus providing consistent signal strength for users in the whole covered area. To realize a shaped pattern inheriting the low cost and simplicity merits of beam-switching array, limited elements (four in this design) are used to form this flat pattern as compared to traditional solutions [8], which is the least requirement for beam shaping. Freedoms lie in elements space, which is commonly used to lower the sidelobe level [9], and are utilized to realize beam shaping. A planar feeding network is designed to drive this array, and a prototype is built and tested in 5.3–5.5 GHz. The corresponding simulation and measurement results are given in this letter.

II. Beam Shaping and Synthesis Algorithm

In traditional beamforming theory, the synthesis process is mainly based on an equally spaced linear array with fully adjustable phase and amplitude distribution. The feed network uses phase shifting at each element to steer a beam into a given angle and further utilizes amplitude control to realize pattern shaping. If an array is placed in the y-axis, a pattern formed in the yz-plane can be given as a fully adjustable weighting factors vector multiplication by a space distribution vector

$$P(\theta)=P_{\mathrm{e}}(\theta)P_{\mathrm{a}}(\theta)=P_{\mathrm{e}}(\theta)\begin{bmatrix}A_1e^{j\varphi_1}\\A_2e^{j\varphi_2}\\\vdots\\A_ne^{j\varphi_n}\end{bmatrix}^T\begin{bmatrix}e^{j2\pi(d_1/\lambda)\sin(\theta)}\\e^{j2\pi(d_2/\lambda)\sin(\theta)}\\\vdots\\e^{j2\pi(d_n/\lambda)\sin(\theta)}\end{bmatrix} \quad (1)$$

where $P_{\mathrm{e}}(\theta), P_{\mathrm{a}}(\theta)$ are the element pattern and array factor, respectively, in angular position θ at the wz-plane, and $A_ne^{j\varphi_n}$ and d_n represent the nth element complex weighting factor and distance from central position, respectively.

Comparatively, the beam-switching array is simplified, and its feed network is commonly based on an $N \times N$ butler ma-

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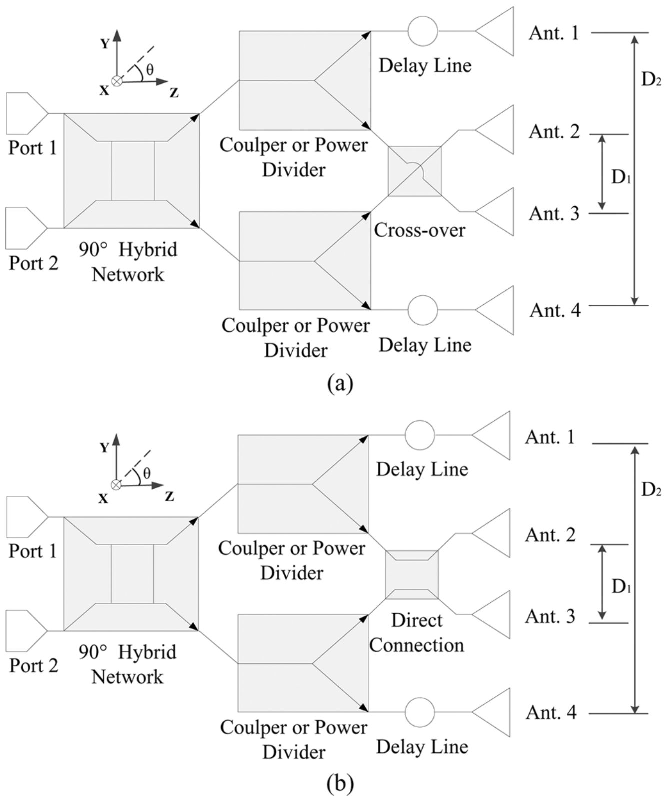


Fig. 1. Two schemes of feeding structure. (a) Scheme 1: Swap phase in central group. (b) Scheme 2: Direct connection in central group.

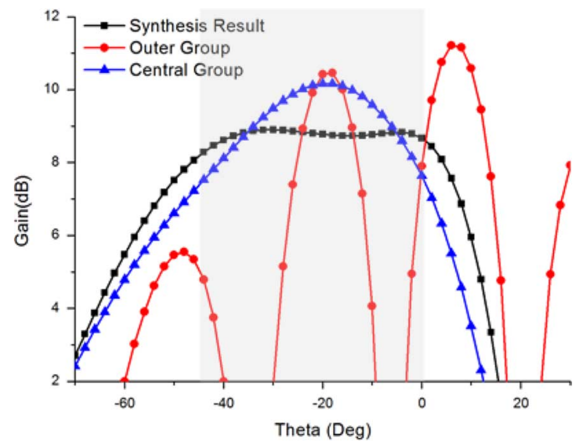


Fig. 2. Simulated synthesis process in HFSS for port 1.

trix, which relies on a hybrid network to divide power and recombine output phase into a desired order for different input ports. Since the power in this structure is equally divided and the phase combination can only steer the array's beam into a specific predetermined direction, no more freedoms can be utilized to realize beam shaping as given in (1).

In this design, in order to realize beam shaping, additional freedoms in a beam switching array are exploited. Based on the traditional 2×2 hybrid network, two power dividers are introduced to implement a 2×4 feeding structure as presented in Fig. 1. Since phase distribution in hybrid network is reciprocal, two schemes, differing in whether the phase in the central two elements is swapped via crossover or not, can be adopted. Retaining the beam-steering function as a traditional beam-switching feeding network, these proposed structures provide flexible amplitude and phase distribution among elements. These four elements can be divided into two groups, named central group with antenna 2, 3 and outer group with antenna 1, 4, whose amplitude and relative phases can be adjusted independently by changing the network's parameters. Moreover, considering that the weighting factors are still subject to symmetric restrictions such as a switching array, freedom laying in array structure is utilized to break through the barrier. By virtue of adopting only four elements in this scheme, the space D_1 in the central group and D_2 in the outer groups can be adjusted individually to modify the space distribution vector in (1), which can acquire more flexibility compared to the equally spaced switching array.

Accordingly, (1) can be rewritten as (2), where weighting factors w in both schemes for input port 1 are provided. For input port 2, the weighting factors have the same elements but with the reversed order

$$P(\theta) = P_{\mathrm{e}}(\theta)P_{\mathrm{a}}(\theta) = P_{\mathrm{e}}(\theta)w^T \times \begin{bmatrix} e^{j\pi(D_2/\lambda)\sin(\theta)} \\ e^{j\pi(D_1/\lambda)\sin(\theta)} \\ e^{j\pi(D_1/\lambda)\sin(\theta)} \\ e^{j\pi(D_2/\lambda)\sin(\theta)} \end{bmatrix}$$

$$w_{\mathrm{scheme1}} = \begin{bmatrix} A_1 e^{j\varphi_1 + \pi/2} \\ A_2 e^{j\varphi_2} \\ A_2 e^{j\varphi_2 + \pi/2} \\ A_1 e^{j\varphi_1} \end{bmatrix} \quad w_{\mathrm{scheme2}} = \begin{bmatrix} A_1 e^{j\varphi_1 + \pi/2} \\ A_2 e^{j\varphi_2 + \pi/2} \\ A_2 e^{j\varphi_2} \\ A_1 e^{j\varphi_1} \end{bmatrix}. \tag{2}$$

Except for the intragroup distance, these two groups are identical with 90° intraphase difference and can generate their own patterns independently by adjusting the intragroup distance D_1, D_2 in both schemes. Thus, the final shaped pattern can be seen as the overlapping result produced by these two patterns, and the intensity of superposition can be adjusted by changing amplitudes A_1, A_2 along with their relative phase difference $\varphi_1 - \varphi_2$.

The synthesis process can be accepted as a combinatorial optimization process. Considering that limited parameters are optimized, an enumeration algorithm is implemented and can be fulfilled with three steps.

1) Find the initial parameters: In this step, the initial value can be found manually as depicted in Fig. 2. A main pattern whose peak points to $\pm 22.5°$ is formed by adjusting D_1 in the central group. Then, a supplementary beam, which is used to facilitate cancellation and compensation, is shaped by tweaking D_2 in outer group. Since D_2 is larger than one wavelength, grating lobes with reverse phases to its adjacent lobe would appear. Thus, it is possible to use this supplementary beam to cancel the main pattern in the peak region while enhancing the margin part with its grating lobe. The initial value is yielded where the relative positions and phases of the two patterns are set appropriately.
2) Optimized with the enumeration algorithm: With the initial parameters given in step 1, an enumeration optimization process is performed in MATLAB. The element pattern information $P_{\mathrm{e}}(\theta)$ simulated in HFSS is imported into MATLAB first, and pattern multiplication method is applied directly since the mutual coupling can be well

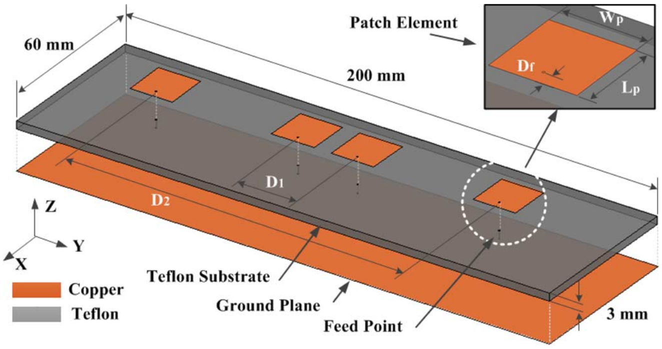


Fig. 3. Structure of proposed array.

TABLE I
OPTIMIZED PARAMETERS OF THE PROPOSED ARRAY

Parameter	φ_1	φ_2	A_1	A_2	D_1 (mm)	D_2 (mm)	SLL(dB)
Scheme I	0°	40°	0.17	1	22.4	128.8	-8.86
Scheme II	0°	70°	0.20	1	22.4	183.8	-8.23

controlled by adopting horizontal aligned vertically polarized elements. The weighting parameters, including intragroup distance D_1, D_2, amplitude A_1, A_2, and relative phaseφ_1, φ_2 are processed in a discrete way and set around the initial parameters. The optimization is guided by (3), and optimal parameters would yield after the enumeration process finished

$$P_{\rm goal}(\theta) = \min\{\max(P(\theta)) - \min(P(\theta))\}|_{0^\circ < \theta < \pm 45^\circ} . \tag{3}$$

3) Fine-tune in HFSS: In this step, optimized results obtained in step 2 are picked out and imported back into HFSS for fine-tuning. The mutual coupling and the ground effect are taken into consideration in this step, and the final optimization parameters are given in Table I, where results for both schemes are provided.

Finally, scheme I is chosen for its smaller size. Meanwhile, its normalized sidelobe level (SLL) is -8.86 dB, which is lower than -8.23 dB for scheme II.

III. PROTOTYPE DESIGN

The arrays and the feeding network are designed with the optimization result and structure given in Section II. Both of these are based on planar structures, which are built on Teflon substrates $(\varepsilon_{\rm r} = 2.65, \tan\delta = 0.001)$ with different thicknesses.

A. Configuration of the Array

The prototype array consists of four identical patch elements distributed symmetrically along the xz-plane. The geometry of this array is depicted in Fig. 3, where distances D_1, D_2 are noted for both groups.

The element in this prototype is a pin-fed square-shape ($L_{\rm p} = W_{\rm p} = 15.9$ mm) patch antenna excited with TM_{10} mode via the feed pin. The feed point is located in the center in y-direction and spaced $D_{\rm f} = 5.1$ mm from the y edge, which has been fine-tuned to achieve the desired bandwidth from 5.3 to 5.5 GHz.

B. Configuration of the Feeding Network

According to the scheme described in Fig. 1 and the weighting factor given in Table I, a planar feeding network

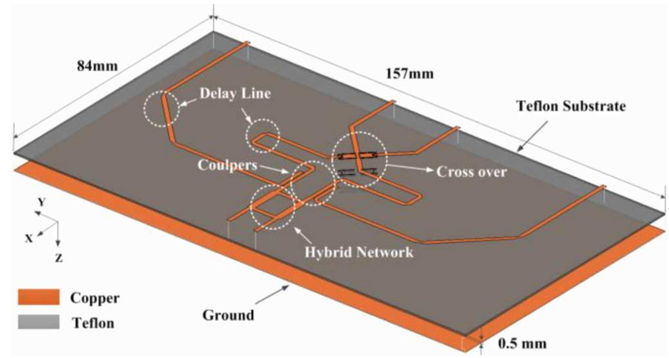
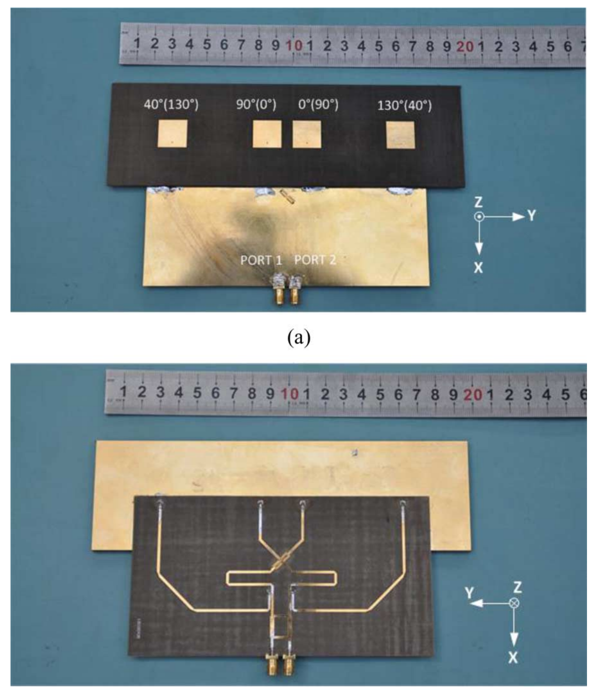


Fig. 4. Structure of feeding network.



(a)

(b)

Fig. 5. Prototype of the proposed array. (a) Front side. (b) Back side.

prototype is designed and presented in Fig. 4. All the components are noted in this figure. Two coupler lines are utilized to implement power division since the ratio is larger than 10 dB $(20\log(0.17))$.

Except for the crossover, the feed network is mirrored along the xz-plane, which generates the desired phase distribution in the four output ports by switching input ports. The crossover, whose structure is given in [10], is configured to realize the phase swapping. Compared to traditional planar crossover realized by a concatenated hybrid network [11], this design can significantly reduce the size of the feed network and acquire consistent performance in a wide frequency range.

IV. SIMULATION AND MEASURE RESULT

With the design given in Section III, a prototype is fabricated, and the photographs are demonstrated in Fig. 5, where a ruler is used as size reference.

In the front side as shown in Fig. 5(a), the array is soldered on the bottom side of the feed network with a good ground contact, and the phase distributions for each element are noted for both

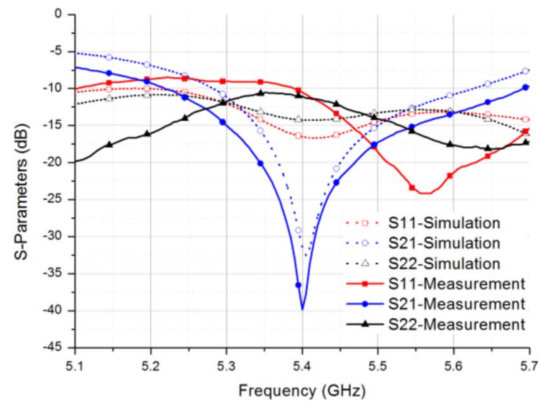


Fig. 6. Measured and simulated S-parameter.

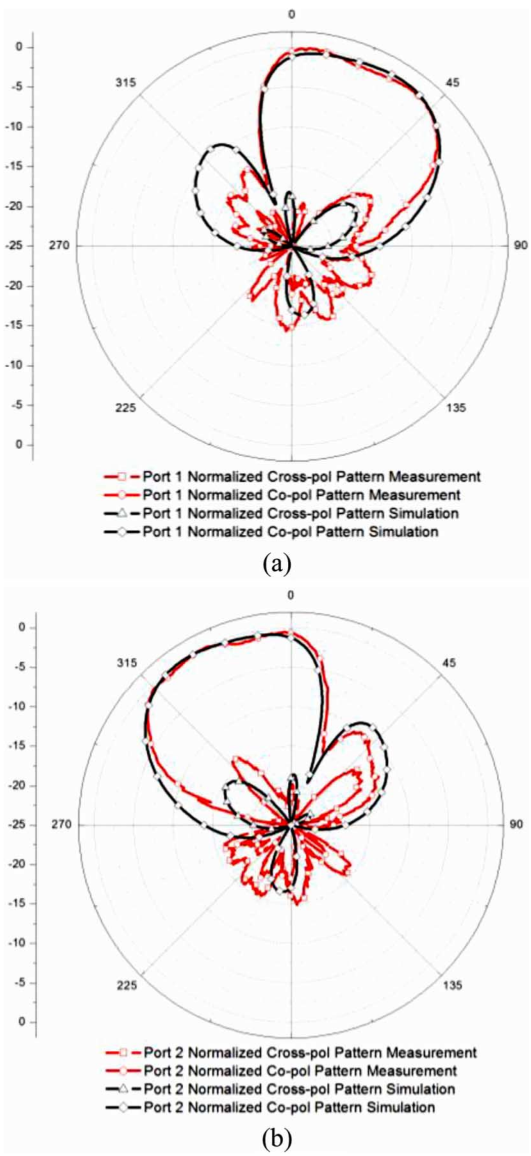


Fig. 7. Measured and simulated pattern of the proposed array in yz-plane. (a) Port 1. (b) Port 2.

input states. At the back side, as displayed in Fig. 5(b), the array's feed points are soldered to the feed line in the feeding network with air jumpers, and two SMA connectors are soldered at the bottom as input ports for this network.

The S-parameters are measured with an Agilent E5017 vector network analyzer (VNA) with two feed lines calibrated by electronic calibration kits. Both the measurement and simulation results are given in Fig. 6. A good isolation between the two ports can be observed around 5.4 GHz, while the measuredS_{11}, S_{22} are slightly higher and distorted as compared to the simulated ones. This may be due to inaccuracy in the fabrication process along with imbalance in the crossover and the tolerance in 50-Ω load for couplers.

The radiation patterns acquired at 5.4 GHz are given in Fig. 7. The simulation is conducted in HFSS, and the prototype array's 2-D pattern in yz-plane is tested in an anechoic chamber. Due to the introduction of extra ground in feed network, the pattern is slightly bent toward the x-direction. Thus, the measured patterns are acquired through 15° tilting from xy-plane and yield less than ± 0.45 dB variation in its 45° coverage for port 1, and ± 0.55 dB in port 2, which are consistent with simulation results of ± 0.55 and ± 0.58 dB, respectively.

V. Conclusion

In this letter, a novel beam-switching array is proposed. A detailed analysis of the synthesis process and the feed networking design are given. The prototype is built and measured, which generates two desired mirrored flat beams covering $0°$–$\pm 45°$ with less than ± 0.55 dB variation. Contrary to traditional beam-switching array, this scheme does not focus on subdividing more sectors with high-gain pencil beams, but pays more attention to realizing a consistent radiation character in each beam, thus providing a stable user experience in the whole area. Compared to traditional beamforming method, this scheme inherits the Butler matrix scheme's aperture co-use idea, and the beam shaping is fulfilled with very limited elements. Thus, the aperture efficiency can be guaranteed, and the optimization process can be simplified to learn clear physical concepts.

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