Multibeam Antenna Based on Butler Matrix for 3G/LTE/5G/B5G Base Station Applications

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Abstract: With the rapid development of mobile communication technology and the explosion of data traffic, high capacity communication with high data transmission rate is urgently needed in densely populated areas. Since multibeam antennas are able to increase the communication capacity and support a high data transmission rate, they have attracted a lot of research interest and have been actively investigated for base station applications. In addition, since multi-beam antennas based on Butler matrix (MABBMs) have the advantages of high gain, easy design and low profile, they are suitable for base station applications. The purposes of this paper is to provide an overview of the existing MABBMs. The specifications, principles of operation, design method and implementation of MABBMs are presented. The challenge of MABBMs for 3G/LTE/5G/B5G base station applications is discussed in the end.

Keywords: multi-beam antenna; base station application; Butler matrix; wideband antenna; multi-band antenna

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1 Introduction

The high-capacity communication is urgently needed in densely populated areas with the fast growth of mobile communication technology and the development of data traffic. In order to increase the channel capacity for mobile communications, two main typical methods are usually employed. One is to improve the frequency bandwidth by employing wideband or multiband antennas[1–5], and the other is to divide a sector into multiple ones by using multibeam antennas[6–23]. Moreover, both the two methods, namely wideband/multiband and multibeam operation, can be simultaneously used to further enhance the communication capacity. For example, to improve the capacity, a conventional sector base station antenna can be replaced by a wideband or dual-band multibeam. In addition, as one of the key technologies of 5G communications, the multi-beam antenna technology, widely employed for 3G/LTE/5G mobile communication and as a potential technology for B5G mobile communication, is able to provide high data transmission rate, improved signal-to-interference-plus-noise ratio, increased spectral and energetic efficiency, and versatile beam shaping[24].

To realize the design of a multibeam antenna, several typical methods have been employed. One approach is to employ a reflector antenna. Multiple beams radiated at different angles can be easily obtained by placing multiple feeds at different positions in front of a reflector antenna[6–10]. Another method is to use a lens antenna[11–14]. When a lens is excited by multiple feeds in different points, the propagation direction of the electromagnetic wave can be changed by the focusing or reflection function of the lens, thus generating multiple radiation beams[15–17]. However, reflector-based and lens-based multibeam antennas suffer from large dimensions, which are generally suitable for millimeter wave frequencies, while not suitable for sub 6 GHz base station applications. Since multibeam antennas fed by Butler matrix have advantages of high gain, low profile and simple structure [18–24], they are expected to be an effective solution of multi-beam antenna for 3G/LTE/5G/B5G mobile communication systems.

In this paper, the multi-beam antennas based on Butler matrix (MABBM) technologies are reviewed. This paper is organized as follows. In Section 2, the specifications for base station applications are discussed. In Section 3, the principles of operation and design approach of MABBMs are provided. Section 4 discusses the latest research progress of MABBMs for mobile communication systems. Section 5 presents the challenges and Section 6 gives the conclusions.

2 Specifications for Base-Station Applications

For practical base station applications, several important specifications of an MABBM should be required. The first one is that the multiple beams need to exhibit stable 10 dB beam width of around 120° in the horizontal plane to realize good coverage. The second specification is that the cross level between adjacent beams is required to be around −10 dB for good communication, as observed in **Fig. 1**. If it is too high, the signals from two sectors will overlap, which will cause continual handoff. On the contrary, the good coverage is not guaranteed if the cross level is too low. The third specification is that the side lobe and grating lobe for each beam should be suppressed in a low level, to reduce signal interference with neighbor beams. Therefore, MABBMs with such performances over a multiple frequency or wide frequency band are in urgent need to meet the application requirements of base stations in densely populated areas.

3 Design Principle and Method of MABBMs

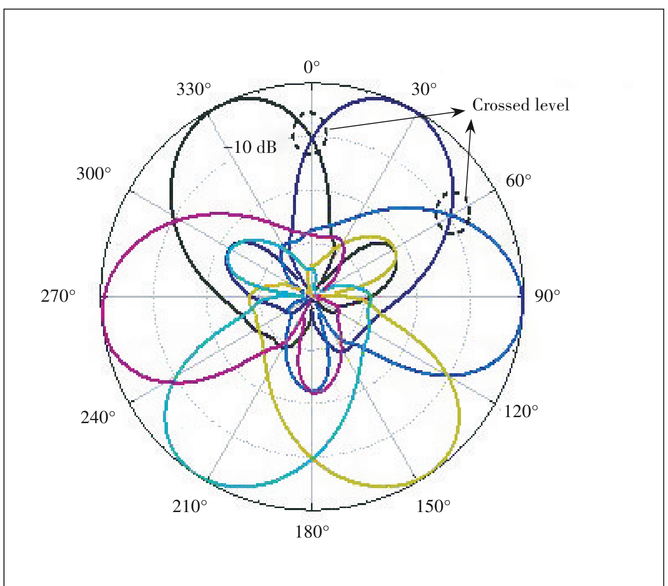
As a kind of passive multiport network, Butler matrix[25–27] has advantages of multiple phase differences, low loss, low profile and simple structure, which has been widely employed as antenna feeding network for multi-beam radiation. When an $N \times M$ Butler matrix is connected to an antenna array with M elements, N independent beams with different directions can be produced as the input ports are excited simultaneously. The principles of operation and design method of multi-beam antennas based on Butler matrix are described in detail below.

3.1 Principles of Operation for MABBMs

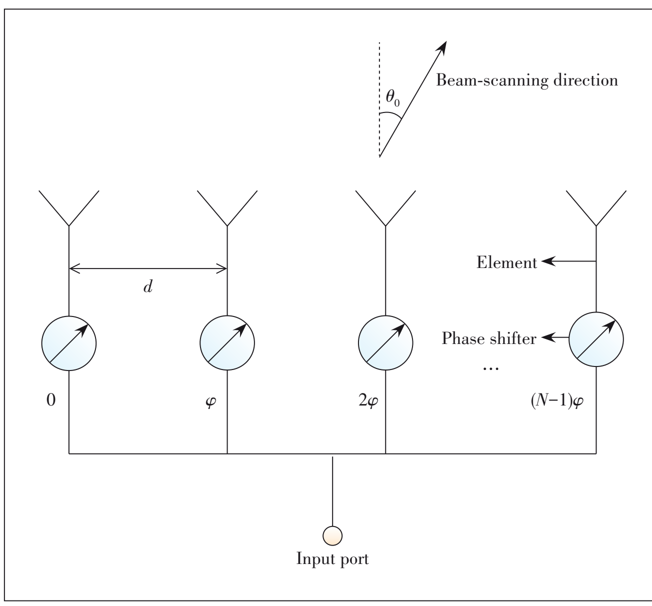
The beam-scanning theory of the antenna array is used to analyze the working mechanism of an antenna array for generating multi-beam radiation, which can be employed to guide the comprehensive design of MABBMs. According to the comprehensive theory of antenna array[28], the beam-scanning angle θ_0 of a linear antenna array can be calculated as follows.

$$\theta_0 = \arcsin\left(-\frac{\varphi\lambda}{2\pi d}\right), \tag{1}$$

where φ and d represent the phase difference and spacing between adjacent elements respectively, and λ represents the wavelength associated with the working frequency in vacuum, with the schematic diagram shown in **Fig. 2**. According to Eq. (1), it is seen that the beam-scanning direction of the antenna array is determined by the wavelength λ corresponding to the operating frequency of the antenna, the phase difference φ and the spacing d between adjacent elements. When the working frequency and spacing are selected, the



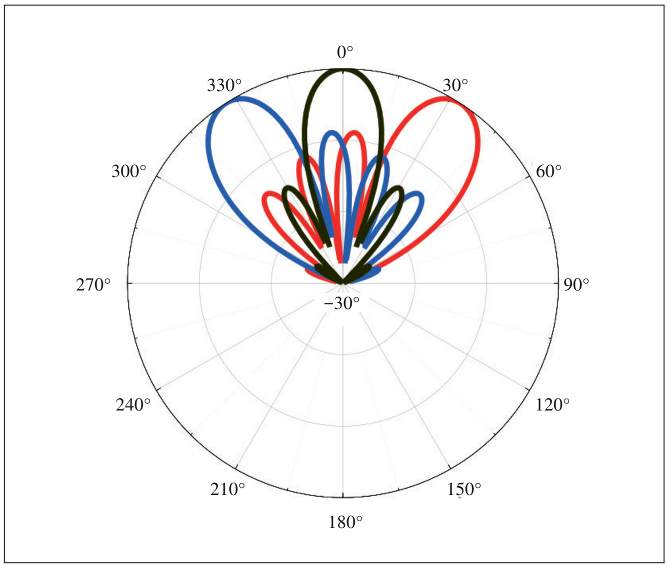
▲**Figure 1. Tri-sector base station scenario.**



▲**Figure 2. Beam-scanning of a linear array.**

beam-scanning direction of the array is only determined by the phase difference of adjacent elements, and different phase differences produce different beam-scanning directions. Therefore, when multiple signals with different phase differences excite an antenna array simultaneously, the antenna array can radiate multiple beams with different directions, realizing multi-beam radiation.

Fig. 3 shows the radiation pattern of a three-beam antenna array fed by a 3 × 5 Butler matrix at 2.2 GHz. The element is a half-wavelength electric dipole, and the spacing between elements is 75 mm. The excitation of the array has equal amplitude and phase differences of −120°, 0°, +120°. It can be seen that 3 beams with different directions have been successfully produced for the MABBM.



▲**Figure 3. Radiation pattern of three-beam antenna array.**

3.2 Design Method of MABBMs

In practical applications, the multi-beam radiation of the MABBMs includes two types: multiple beams in the horizontal plane or in the vertical plane[29–30], and 2D multiple beams in both horizontal and vertical planes[31–33]. In order to simplify the analysis without loss of generality, this paper provides the design method of MABBMs with multiple beams in the horizontal plane. Another type of 2D MABBMs can be designed in a similar way. Generally, a 1D MABBM is mainly formed by an $M \times L$ array, $N \times M$ Butler matrices and L-way power dividers, as shown in **Figs. 4a**, **4b** and **4c** respectively. The design steps of the MABBM can be summarized as follows.

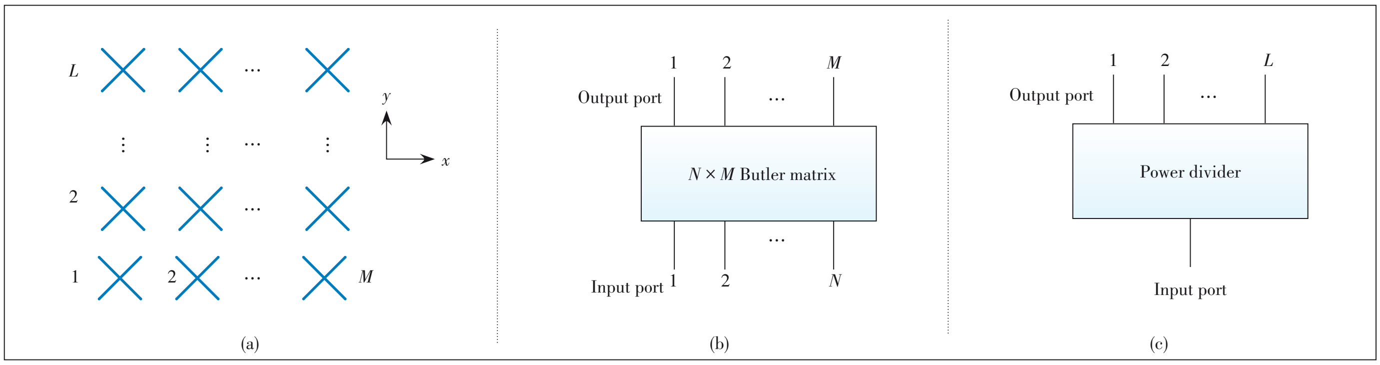
Step 1: Implementing $N \times M$ Butler matrix. Firstly, the numbers (N) of radiation beams of an MABBM and input ports of Butler matrix are determined. The communication capacity is associated with the number of radiation beams, with greater number of radiation beams providing more capacity. The number of radiation beams is obtained by the communication capacity required, which is equal to the number of input ports of Butler matrix. Then the numbers (M) of the output ports of the Butler matrix, and the amplitude and phase difference of the Butler matrix are determined by the side lobe level required for each beam. On the basis above, the $N \times M$ Butler matrix is designed, which will meet the bandwidth, amplitude and phase difference requirements.

Step 2: Designing $M \times L$ array. The number (M) of elements in the horizontal plane of the array is equal to the number of the output ports of the Butler matrix, and the number (L) of the elements in the vertical plane is determined by the required gain. In addition, the spacing between adjacent elements in the horizontal plane plays an important role in the coverage area of the multiple beams and cross level between adjacent beams, which should be carefully selected. On this basis, the antenna element is designed, which will meet the requirement of the needed bandwidth and then the required $M \times L$ array is implemnted.

Step 3: Implementing the MABBM. The output port of each power splitter is connected to the antenna element in the vertical plane through 50 Ω coaxial cables firstly, and then the input port of each power splitter is connected to the output port of the Butler matrix through 50 Ω coaxial cables for implementing the proposed multi-beam antenna.

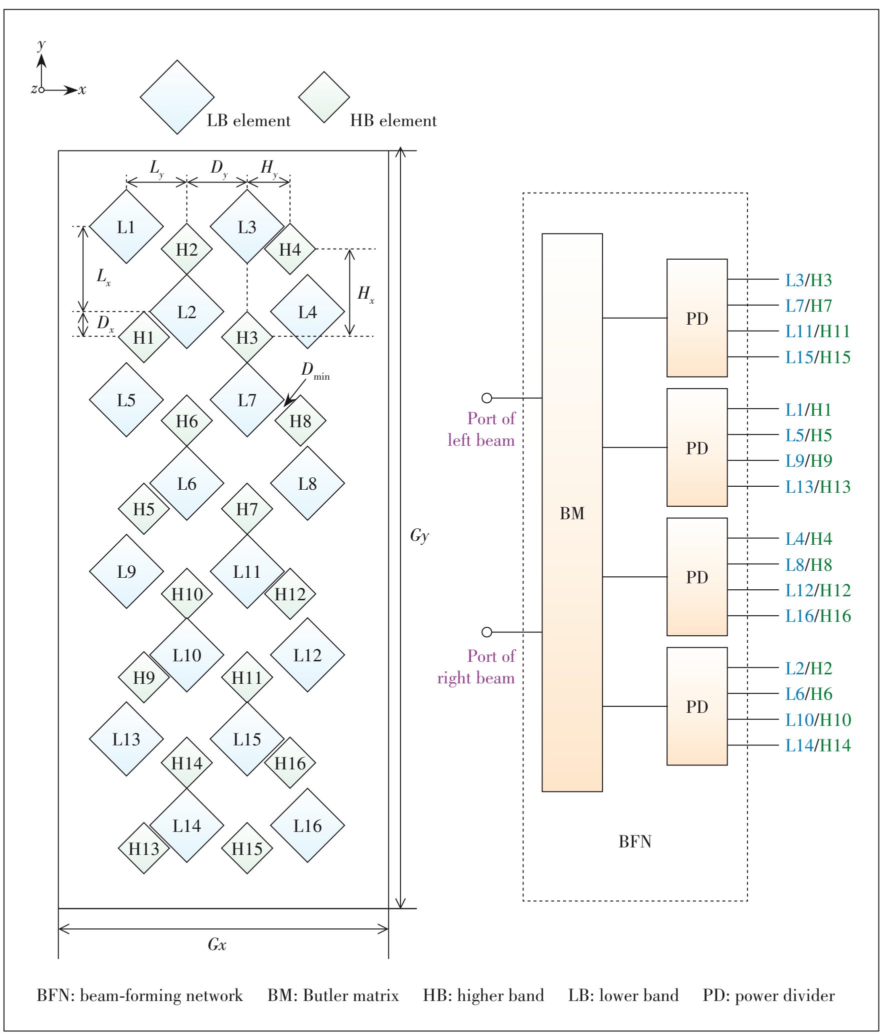
4 Latest Research Progress of MABBMs for Base-Station Applications

Recently, various MABBMs have been proposed for mobile communication applications. In Ref. [34], a compact dual-



▲**Figure 4. Multi-beam antenna based on $N \times M$ Butler matrix with (a) $M \times L$ array; (b) $N \times M$ Butler matrix; (c) power divider.**

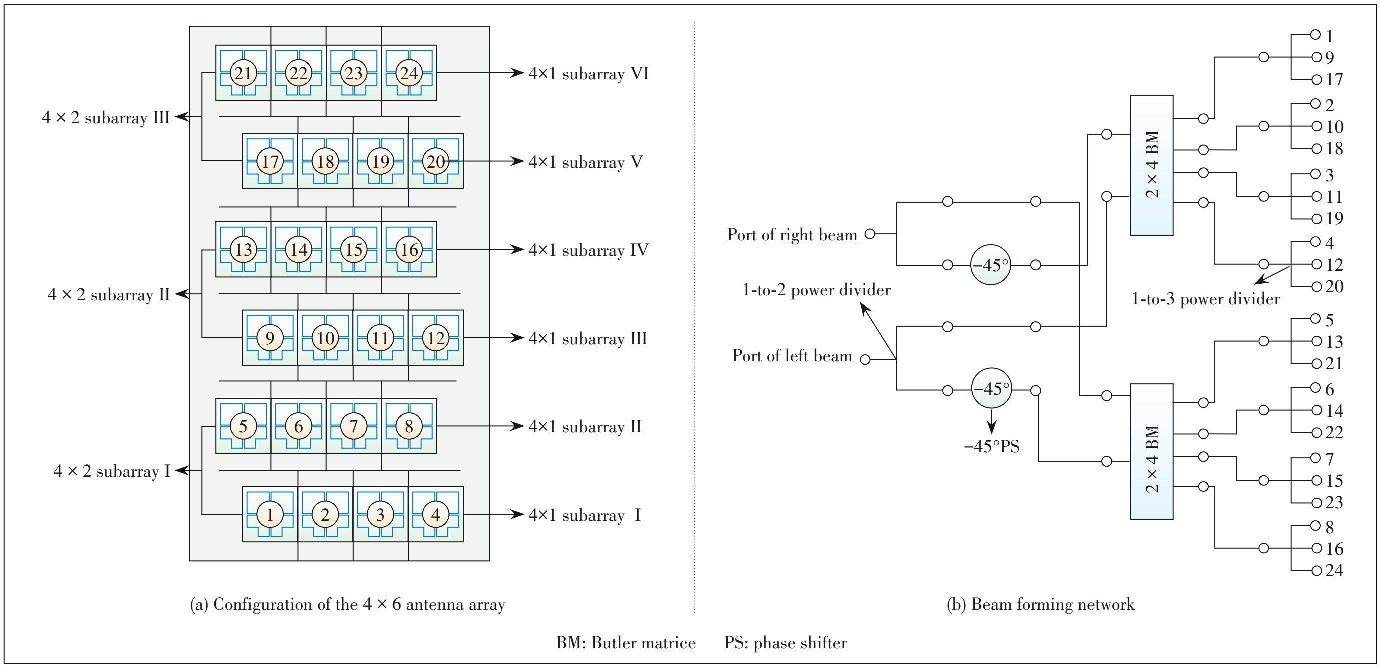
band two-beam 4 × 8 antenna array with dual polarizations for base station applications is proposed. It consists of two 4 × 4 subarrays operating at 3G (1 710 – 2 170 MHz) and long term evolution (LTE) (2 490 – 2 690 MHz) bands. For size miniaturization, the elements of the two 4 × 4 subarrays are interleaved with each other, as shown in **Fig. 5a**. The mutual coupling between the elements operating at different bands is suppressed by using filtering antennas[35] with out-of-band radiation suppression. To obtain stable two-beam radiation patterns within the two operating bands, the beam-forming networks with little magnitude and phase imbalances are specially designed for each band. The configuration of the beam-forming network is illustrated in **Fig. 5b.** It is composed of one 2 × 4 Butler matrix and four filtering power dividers (PDs).The array exhibits a stable 10 dB beam width around 120° in the azimuth plane within the two entire bands, and the two-beam radiation patterns satisfy the coverage requirement of 120° in the azimuth plane for base station applications. Additionally, 16.4 dBi/15.5 dBi peak gains and around −10 dB cross levels at the junction of two beams are achieved within the two operating bands.



▲ Figure 5. Dual-band two-beam antenna in Ref. [34]. (a) Elements distribution of the interleaved configuration; (b) Beam forming network diagram.

In Ref. [36], a wideband dual-polarized 4 × 6 antenna array with two beams for base station applications is provided. It consists of three 4 × 2 subarrays, with the configuration shown in **Fig. 6a**. To obtain ±45° dual-polarized radiation, a wideband crossed dipole is employed as a basic element. For each 4 × 2 subarray, the lower and upper 4 × 1 subarrays are misaligned in the horizontal plane. In this way, the 4 × 2 subarray is equivalent to an 8 × 1 subarray with a half of adjacent element spacing, resulting in good grating-lobe suppression. To achieve stable two-beam radiation with low side lobe over a wide frequency band, specific wideband beam-forming networks with little magnitude and phase imbalances are designed. The diagram of the beam-forming network is plotted in **Fig. 6b**. It consists of two 1-to-2 power dividers, two −45° phase shifters (PSs), two 2 × 4 Butler matrices (BMs) and eight 1-to-3 power dividers. Moreover, the adjacent element spacing is optimized to obtain a stable 10 dB beam width around 120°, thus satisfying the coverage requirement of 120° in the horizontal plane for base station applications. The array exhibits two beams with a stable 10 dB beam width around 120° in the horizontal plane and around −10 dB cross level between two beams. The impedance bandwidth is measured to be 56.1% (1.64 – 2.92 GHz) for voltage standing wave ratio (VSWR) <1.5 and horizontally side-lobe and grating-lobe levels of the two beams are measured to be better than 18 dB.

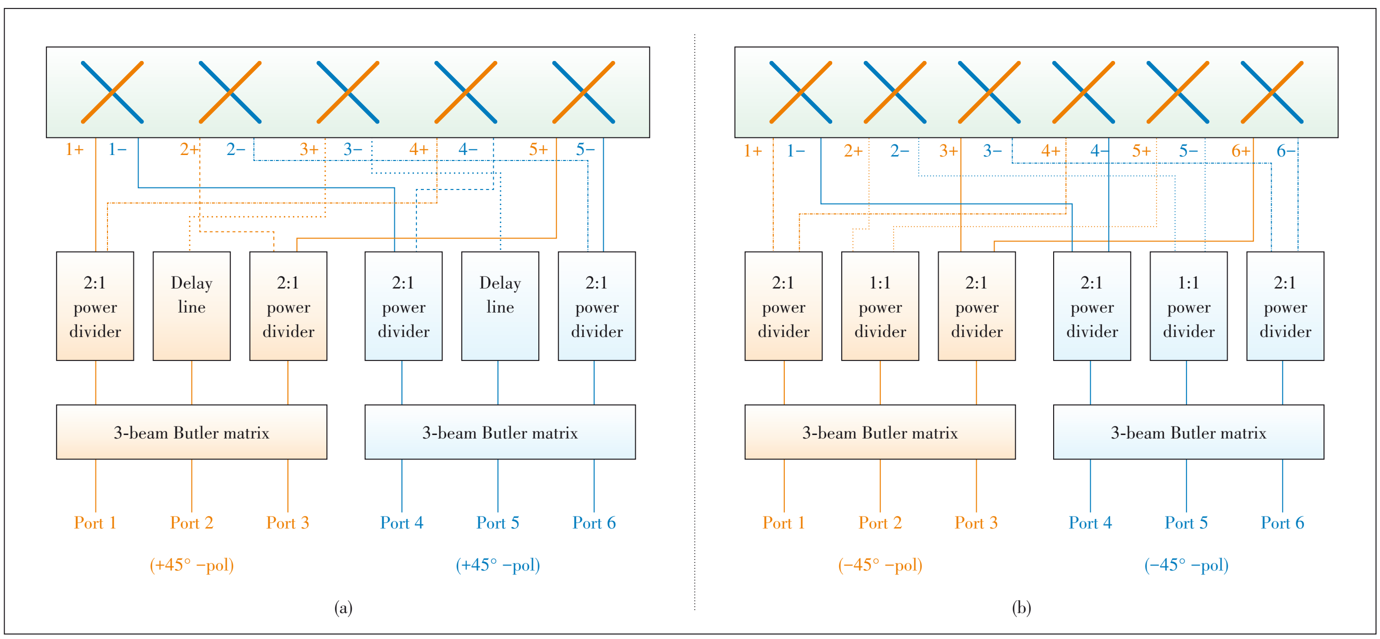
In Ref. [37], broad band three-beam antenna arrays based on Butler matrices are presented, which are employed to increase the capacity of 3G/LTE base stations. The essential part of the three-beam arrays is a wideband 3 × 3 Butler matrix, which is formed by quadrature couplers and fixed wideband phase shifters. Wideband quadrature and phase shifters are implemented by strip lines. To achieve the suitable beam width and the required crossed level between adjacent beams, beam-forming networks consisting of augmented 3 × 3 Butler matrices and power dividers are proposed to expand the number of output ports from three to five or six, as shown in **Figs. 7a** and **7b** respectively. Dual-polarized, three-beam antenna arrays with five and six elements covering 3G/LTE band are developed with good impedance matching, high isolation between beams, and three-beam radiation in the horizontal plane over the wide frequen-



(a) Configuration of the 4 × 6 antenna array (b) Beam forming network

BM: Butler matrice PS: phase shifter

▲**Figure 6. Wideband two-beam antenna in Ref. [36].**

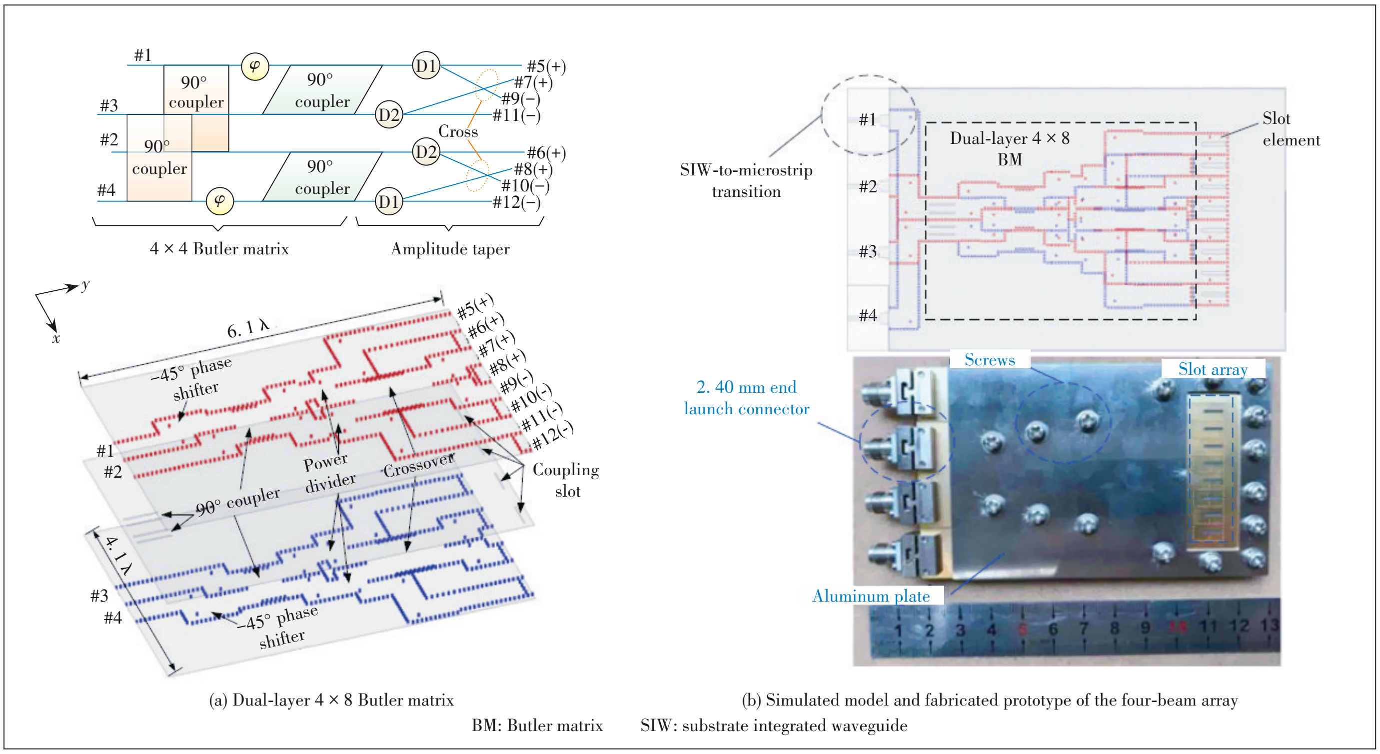


(a) (b)

▲**Figure 7. Three-beam antennas with (a) five elements and (b) six elements in Ref. [37].**

cy band of 1.7 – 2.7 GHz.

In Ref. [38], a compact four-beam slot antenna array fed by a dual-layer 4 × 8 Butler matrix with side lobe level suppression by substrate integrated waveguide technology is proposed. To address the excessive crossovers in the classic 4 × 8 Butler matrix, a novel dual-layer configuration is proposed, which is formed by a 4 × 4 Butler matrix and an amplitude taper, as illustrated in **Fig. 8a.** The 4 × 4 Butler matrix is employed to provide four outputs with equal powers and desired phases, and the amplitude taper is used to convert the four outputs with equal power divisions into eight outputs with unequal power distributions for reducing side lobe level. The proposed topology of the 4 × 8 Butler matrix is employed to reduce the required crossovers from original five sets to merely one set. Therefore, the 4 × 8 Butler matrix can be significantly simplified to achieve better compactness. Finally, a slot antenna array with eight elements is fed by the proposed BM to produce four-beam radiation with low side lobe level, with the



▲**Figure 8. Four-beam array in Ref. [38].**

simulated model and prototype as shown in **Fig. 8b**.

To further increase the communication capacity, a modified topology of a 2D multibeam antenna array[39] fed by a passive beamforming network is proposed by introducing two sets of vertical interconnections into the conventional array configuration. Different from the traditional design, the proposed array structure shown in **Fig. 9** can be integrated into multi-layered planar substrates conveniently, which has advantages of low loss characteristics, ease of realization, and low fabrication cost for millimeter wave applications. A 4 × 4 multibeam antenna array that can generate 16 beams is then designed. The proposed array configuration provides a new means to implement the relatively large size 2D multibeam antenna arrays with planar passive beamforming networks, which would be attractive for future millimeter wave wireless systems used for 5G/B5G communications.

5 Challenges of MABBMs

With the rapid development of mobile communication technology, mobile communication systems are developing towards the trend of broad frequency band, multiple frequency bands, miniaturization, and low cost, which leads to the following challenges for MABBMs.

(1) Design of Wideband or Multi-band MABBMs

In the 5G/B5G era, mobile communication systems such as 2G, 3G, 4G, 5G and B5G will coexist for a long time in the future. In order to comply with the development trend of mobile communication, reduce the number of antennas, and improve the utilization of space resources and spectrum resources, an MABBM is required to cover multiple communication frequen-

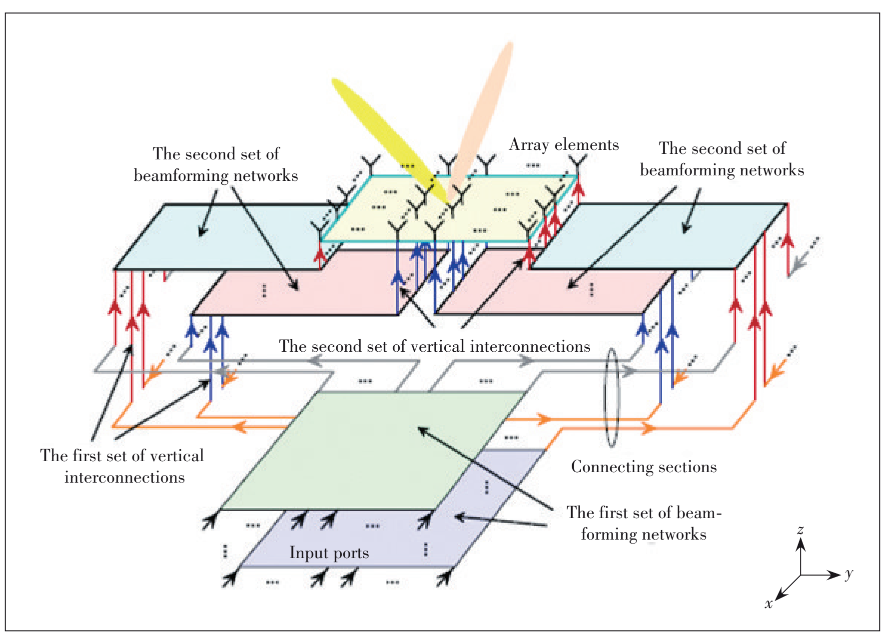


Figure 9. Configuration of the planar 2D multibeam antenna array in Ref. [39].

cy bands. Therefore, a broadband or multi-band MABBM with good impedance matching, high beam isolation, and excellent side lobe suppression is a major challenge.

(2) Miniaturization of MABBMs

Miniaturized MABBMs can not only reduce the spacing of mobile communication system, but also decrease the associated cost. In order to achieve miniaturization of MABBMs, it is necessary to narrow the distance between antenna elements and reduce the size of the Butler matrix. This would introduce strong electromagnetic coupling and radiation interference, causing problems such as deterioration of beam solation and distortion of radiation pattern. Therefore, miniaturization of a MABBM with good electrical performance and radiation performance is another challenge.

6 Conclusions

In summary, the MABBM technologies have been reviewed in this paper. The specifications for base station applications, principles of operation, design and implementation of MABBMs are presented, and the latest research progress on broadband or multi-band MABBMs is analyzed. Even though a few related challenges remain to be solved, the full MABBM is regarded as a promising pathway towards the realization of high-performance 3G/LTE/5G/B5G mobile communication systems.

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