

Investigation of 16-Channel Beam-Forming Network of a Multi-beam Antenna Array for Mobile Communications

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Abstract

A cylindrical multi-beam array for base station of mobile communications is presented. The array is based on a 16-channel beam-forming network of Butler type (modified). The modification allows to produce the circuit on a single-sided microstrip printed-circuit board, to reduce the cost of the module and improve its reliability. The frequency characteristics of the presented beam-forming network have been investigated in the frequency range of 1.6–2.4 GHz. The results are presented in the table and graphs.

1. Introduction

Present-time wide use of mobile communication networks leads to the necessity to increase network capacity and communication quality improvement. One of the promising directions is the using of base stations equipped with multi-beam antenna arrays [1]. In the paper [2] it was proposed to use for these purposes a phased array consisting of 3 panels that form beams independently. Along with the advantage of lower manufacturing cost and high reliability this structure has several drawbacks. Namely, the use of independent panels leads to the less effective use of antenna aperture, worsening of the signal-to-clutter ratio in the crossing area of cells from different panels and forms coverage area of a non-convex shape on the ground surface, which hampers linking to the other analogous base stations.

In the paper [3] there was proposed a base station antenna which is an active phased array with a close to cylindrical form of array. Such antenna forms 19 cells of approximately equal area on the ground surface. The coverage area has hexagonal shape. The size of the coverage area and cells may vary in wide range without changes in antenna structure. Besides, in this research there was proposed a method that makes possible the avoidance of “hanging-up” of side lobes which is typical for nonplanar phased arrays (including cylindrical ones). Use of this method considerably improves the signal-to-clutter ratio which is a problem issue in the development of phased arrays of communication systems.

In this article we review a base station antenna which is a cylindrical multi-beam antenna array based on a beam-forming network (BFN) of Butler type. This approach makes it possible to lower the costs and improve reliability.

2. Parallel 16-Channel Beam-Forming Network

At the embodiment a multi-beam antenna array is a cylinder consisting of $N_\phi=16$ radiating elements in a ring and $N_\theta=8$ radiating elements located along the cylinder generatrices. Average wavelength is $\lambda=15$ cm. Array spacing in a ring is $\Delta_\phi = 0.5\lambda = 7.5$ cm. Ring diameter at phase centers is $D_c = \Delta_\phi N_\phi / \pi = 38.2$ cm. Array spacing along the cylinder generatrix is $\Delta_\theta = 0.7\lambda = 10.5$ cm. Cylinder length $L_\theta = \Delta_\theta \cdot N_\theta = 84$ cm. Total number of elements in the array is $N = N_\phi \cdot N_\theta = 128$ radiating elements.

Cylindrical antenna array consists of the following: 16-channel beam-forming network of Butler type, “herringbone” electric circuit of power division from each output of the BFN to the correspondent radiating element (ring power dividers are used), and radiating elements – half-wave dipoles. 8 radiating elements along the cylinder generatrix form one narrow beam. Main attention is paid to the beam-forming network.

In this article a passive linear 16-channel BFN of Butler type [4-6] is reviewed. The base elements of this arrangement are hybrid rings of 1.5λ length and set of phase shifters. Functional diagram of the investigated BFN shown in Figure 1.

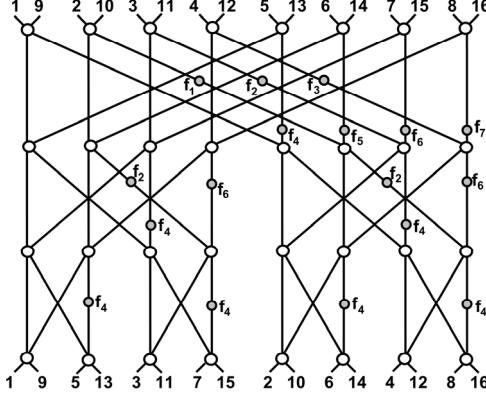


Figure 1 – Functional diagram of the beamforming network.

The numbers at the lower part of the diagram stand for the inputs where the signals that are transmitted to the corresponding beam are received, the numbers at the upper part of the diagram stand for the outputs to which radiating elements are connected. f_k – phase shifters with a phase delay $k^*(-22.50)$ correspondingly.

This BFN of Butler type is modified. It contains 17 phase shifters and standard Butler matrix contains 24 of them. Such modification makes it possible to simplify the arrangement when it is produced on a single-sided microstrip printed-circuit board, to reduce the cost of the module.

In this scheme microstrip segments of transmission lines with different length are used as phase shifters.

3. Study of Frequency Characteristics of a Beamforming Network

The calculation of external characteristics of the BFN was performed with the use of scattering matrix. For estimation of total scattering matrix of the hybrid ring which is an eight-poles with one simple geometric symmetry the method of decomposition of symmetrical eight-poles was used (method of in-phase and antiphase excitation) [5]. Scattering matrixes of partial quadripoles of in-phase and antiphase excitation were determined independently through transmission matrixes product. Half of the hybrid ring as a partial quadipole is a chain of elementary stages each with its own transmission matrix.

The calculation was carried out as follows:

1. The scattering matrix of the hybrid ring is calculated;

2. The scattering matrix of a phase shifter is calculated: $s = \begin{bmatrix} 0 & e^{-j\beta l} \\ e^{-j\beta l} & 0 \end{bmatrix}$, where l is the length of line,

$\beta = 2\pi/\lambda$ is a wave number;

3. Hybrid rings are joined into a bar (first line of the elements at the bottom of the diagram, figure 1), thus a scattering matrix of a 64-pole with 32×32 dimension is formed;

4. The second bar is a 64-pole consisting of joint transmission lines and phase shifters (the next line of elements in figure 1); and so on, 7 bars in total;

5. The obtained bars (matrixes 32×32) are joined in the same sequence as they are situated in the diagram using the method of calculation of cascade connection of two multipoles with known scattering matrixes.

As a result, the scattering matrix $S_{i,j}(f)$ of the BFN is calculated depending on the frequency. The losses brought in by base elements and transmission lines were not taken in consideration in the program. The calculation of the frequency characteristics of the 16-channel beam-forming network was carried out in the range of 1.6–2.4 GHz.

Due to the elements of scattering matrix it is possible to evaluate the following characteristics of the beam-forming network: input standing-wave ratios (SWR) $K_l = (1 - |S_{l,l}|) / (1 + |S_{l,l}|)$ and coupling coefficients (CC) $L_{i,j} = -20 \cdot \lg(|S_{i,j}|)$, where l, i – input numbers; j – output numbers, $i \neq j$. Frequency dependences K_l and $L_{i,j}$ are displayed in figures 2 and 3 correspondingly.

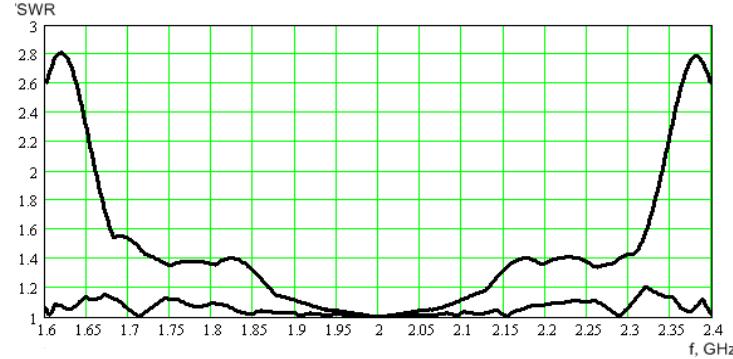


Figure 2 – Possible values of standing-wave ratio in the frequency range at all inputs of the BFN. Upper line – maximum value of SWR at all inputs, lower line – minimum value of SWR at all inputs.

The area in figure 2 shows the borders of the frequency range.

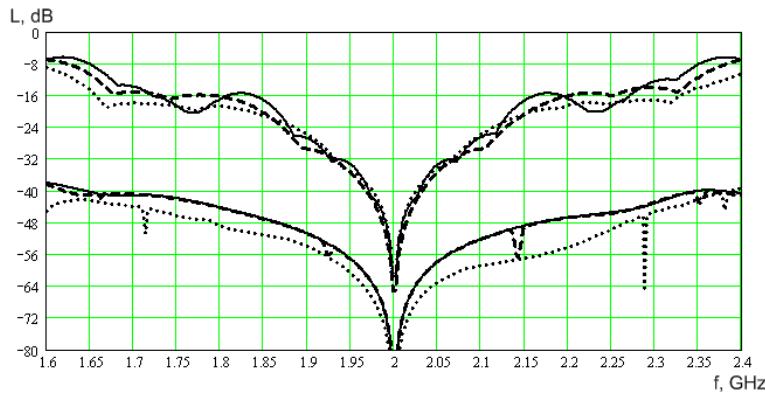


Figure 3 – Possible values of coupling coefficients L (values of coupling coefficients at 2 GHz were not taken into consideration). Solid line indicates minimum and maximum values of CC at input 1, dashed line indicates CC values at input 2, dotted line indicated CC values at input 3.

Amplitude and phase distributions at the outputs of the beam-forming network, representing $|S_{i,j}|$, are shown in figures 4 and 5 correspondingly.

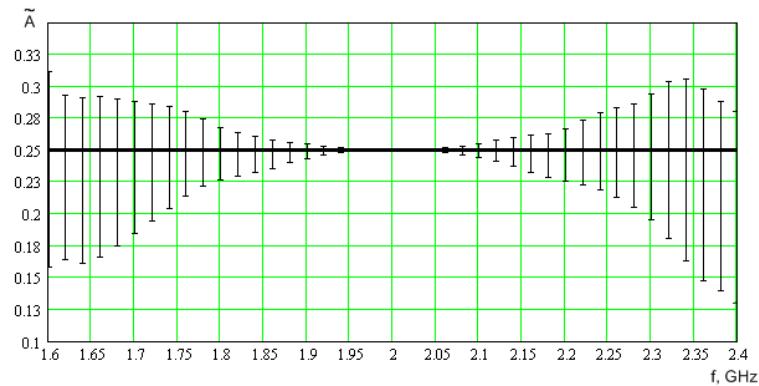


Figure 4 – Possible values of the amplitude in the frequency range by signal injection to input 1.

Vertical segments stand for intervals of maximum divergence of amplitude \tilde{A} at all 16 outputs, from initial amplitude value 0.25.

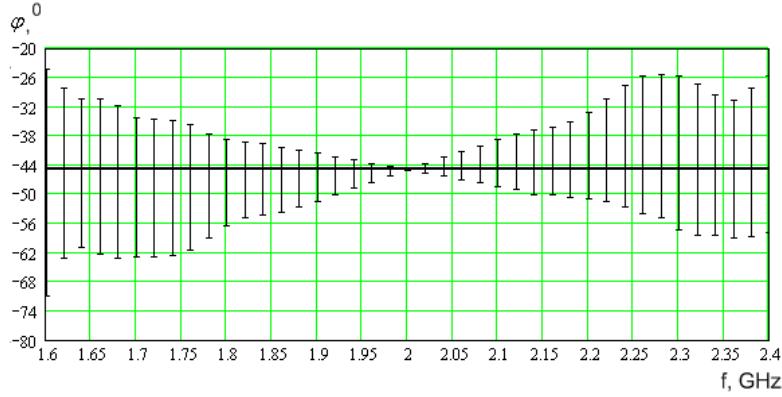


Figure 5 – Intervals of phase φ spread at all outputs depending on the frequency.

The obtained intervals of phases shift values lead to limitation of the used frequency range as well. The results of modeling of all the studied characteristics are displayed in table 1.

Table 1

Frequency band, %	10		20		30		40	
Frequency, GHz	1.9	2.1	1.8	2.2	1.7	2.3	1.6	2.4
SWR	1.15	1.15	1.37	1.38	1.52	1.42	2.6	2.6
CC, dB	-24	-24	-16	-16	-13.6	-12	-7.2	-7.2
Interval of amplitude divergence	[0.244, 0.256]	[0.244, 0.256]	[0.23, 0.271]	[0.23, 0.271]	[0.198, 0.295]	[0.197, 0.297]	[0.162, 0.315]	[0.127, 0.286]
Interval of phase spread	[−41°, −51°]	[−37°, −49°]	[−39°, −57°]	[−34°, −33°]	[−34°, −63°]	[−26°, −58°]	[−24°, −71°]	[−26°, −57°]

4. Conclusion

A 16-channel beam-forming network of a cylindrical multi-beam antenna array for mobile communications network (a modified Butler matrix) has been reviewed in the article. There has been carried out its computer modeling and the study of its frequency characteristics.

In table 1 the results of numerical calculations are given. By them one can judge about the limitation of the frequency range.

One of the variants of the frequency dependence reduction is the replacement of base elements (hybrid rings) by other structures of cross-couplers, which will make it possible to widen the frequency range of the proposed scheme.

When microstrip transmission lined are used as phase shifters, phase deviation may differ from the set value greatly, which leads to distortion of the whole phase picture at the outputs of the beam-forming network. To minimize this effect it is possible to use other types of phase shifters, e.g. Schiffman phase shifters.

References

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