A Biconical Multibeam Antenna for Space-Division Multiple Access

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***Abstract*—The biconical antenna is well known as an easy to build broad-band antenna with omnidirectional radiation. In this paper, the biconical antenna is modified for selective radiation in azimuth direction. By enlarging the diameter of the coaxial feed to the biconical antenna, a set of higher order modes can be excited. In addition to the angular independent TEM mode, higher order TE-modes are also allowed for propagation, which result in an angular dependent far-field pattern. Several features of this multimode excitation are of interest. Applying multiple input feed connectors allows simple rotation of the antenna beam by switching or, when independently operated, transmission and reception for communication in different angular directions for real-time space division multiple access (SDMA). As with conventional antenna arrays, adaptive pattern synthesis can also be realized by using multiple input feed connectors in combination with an appropriate amplitude and phase shifting network. The antenna allows an extremely flexible design of its characteristics at low cost, both requisites for SDMA communication.**

***Index Terms*—Biconical antennas, multibeam antennas.**

I. Introduction

RADIO communication systems are limited to a four-dimensional space. To share this space among multiple communication partners, its dimensions frequency, time, code, and space must be used to separate the various radio services from each other. Currently, existing radio communication systems usually make use of frequency division multiple access (FDMA) and time division multiple access (TDMA); some newer systems also implement code division multiple access (CDMA).

For future systems, multiple access by space division multiple access (SDMA) will be of higher importance for the increase of network capacity and reduction of interference. In a mobile communication network, this results in a directional communication from the base station, which transmits and receives RF power only in the direction of the mobile station. An omnidirectional broadcast mode ensures the channel assignment for new active mobiles. SDMA will be able to reduce channel interference and multipath, while power efficiency and network capacity will be increased at the same time.

The required radiation modes for SDMA are classified as follows:

- broadcast mode (360° azimuth);
- selective directional beams:
  a) practically up to four beams;
  b) independent operation of the beams;
  c) maximum two at the same frequency channel;
  d) low side lobes;
  e) real-time switching for TDMA.

For the determination of the desired beam directions, an SDMA processor at the base station calculates the optimum azimuth angle from the incoming multipath signal from the mobile in the broadcast mode. This processor is not part of this paper, the desired directions are assumed to be known.

SDMA, the challenging topic in communication, was defined otherwise as a task in radar systems many years ago. Keywords in radar technique around this problem are phased arrays, track-while-scan, adaptive nulling, multimode, and so on. The differences in the specifications for SDMA in communications to radar antenna engineering are mainly as follows:

- no elevation scan is required;
- the antenna gain only needs to be around 20 dB;
- radiation pattern sidelobes up to -20 dB are allowed;
- polarization purity less than -17 dB;
- extremely low cost is mandatory;
- a limited number of inputs/outputs is required;
- limited to small sizes of several wavelengths.

The above requirements exclude (for communication purposes) standard techniques in radar like Butler matrices [1] or lenses [2]. In communications, each frequency channel has to be separately processed through a receiver at each SDMA antenna port. Switching of a single receiver to the appropriate port is usually excluded because of simultaneous operation across 360° azimuth. It can be expected that this problem will become less severe as soon as direct digital downconversion is available for mobile communication frequencies.

In the following approach, an antenna design is introduced, which has special signal processing capabilities similar to lenses integrated in the antenna structure, therefore, no external feed network is necessary. It is a modified construction of the well-known biconical horn antenna. Biconical horn antennas have been used as multioctave broad-band antennas with omnidirectional radiation patterns in the H-plane for many applications in the past [3]. In that case, the biconical waveguide is excited by a TEM mode, as illustrated in Fig. 1(a). Electric and magnetic field vectors are independent of the azimuth, resulting in the uniform radiation pattern in the H-plane. The TEM-mode is coupled via the feeding coaxial waveguide.

Besides the TEM mode with angle-independent fields also TE and TM modes are allowed for propagation in an overmoded coaxial waveguide, where especially the nonrotationally symmetric modes are of interest, Fig. 1(b). By linear

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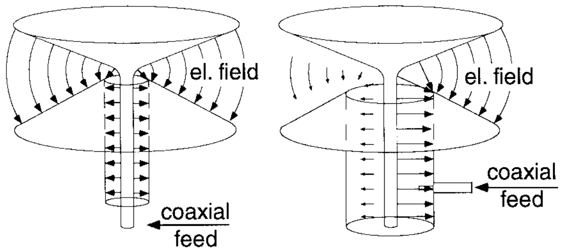
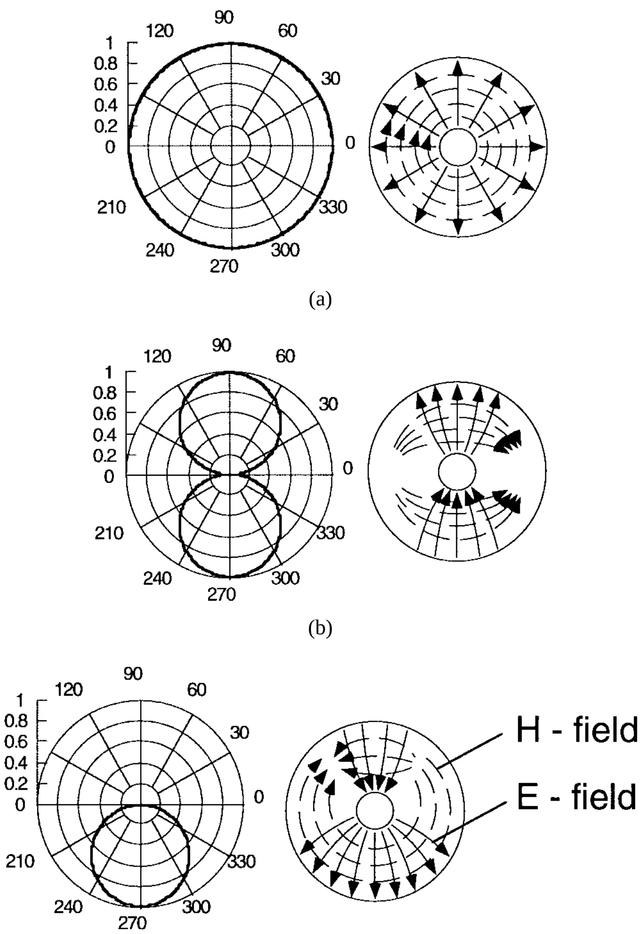


(a) (b)

Fig. 1. (a) Biconical antenna excited by the TEM-mode, electric field shown. (b) Biconical antenna excited by superposition of TEM and TE_{m1} modes.



(a)

(b)

(c)

Fig. 2. Linear superposition of coaxial TEM and TE_{11} modes and effect on the far-field pattern. Left diagrams: intensities, right diagrams: schematic field distributions. (a) TEM mode. (b) TE_{11} mode. (c) TEM $+\mathrm{TE}_{11}$ modes.

superposition of the TEM mode and additional TE_{m1} modes in the feeding coaxial waveguide, the resulting electric and magnetic fields in the aperture are functions of the azimuth angle.

An example for the superposition of the coaxial TEM and TE_{11} modes is given in Fig. 2(a)–(c). While excitation of the biconical antenna with the TE_{11} mode only results in a bidirectional antenna pattern (in the shape of an "8"), superposition of both modes gives a cardioid radiation pattern, as the fields of the two modes are in phase in the forward direction and 180° out of phase in backward direction.

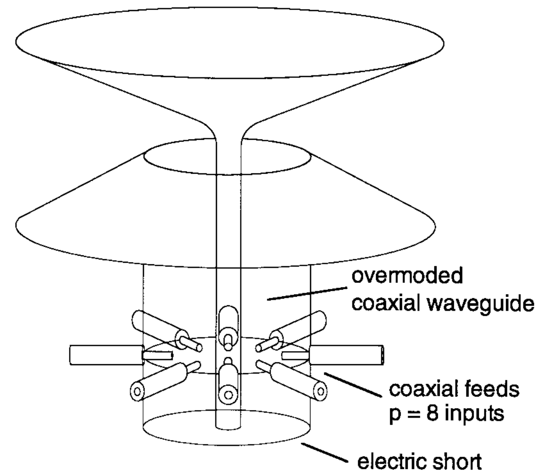


Fig. 3. Mechanical realization of the biconical antenna with multiple feeds.

II. Functional Parts of the Antenna

The mechanical realization of the overmoded biconical antenna can be seen in Fig. 3. The coaxial feed connectors for the higher order modes are placed around the azimuth in the coupling region. Each of them excites the same number of modes, but with an angular offset. The dimensions of the coaxial waveguide determine, which modes can propagate at a given frequency. The lower end of the coaxial waveguide is terminated either by an electric short, or by an absorber. The upper end is connected via the transition zone with the biconical waveguide. The superposition of the electric and magnetic fields in the aperture surface determines the radiation patterns in the far-field of the antenna.

A. Overmoded Coaxial Waveguide

The overmoded coaxial waveguide with the feed lines is the heart of the described antenna, as its dimensions determine, which modes can be excited at a given frequency. It is also the location of the linear mode superposition, i.e., where the "beamforming" takes place. Apart from the TEM mode, all other TE and TM modes can only propagate in the coaxial waveguide above their cutoff frequency. A graphical overview of the cutoff frequencies of the coaxial waveguide versus r_i/r_o for $r_o = 15$ mm is shown in a mode chart in Fig. 4.

For superposition with the TEM mode especially the TE_{m1} modes are of interest, which will only be considered in the following. Their radial electric field components E_r and azimuthal magnetic field components H_φ are parallel to the fields of the TEM mode. The fields are harmonic functions of the azimuth angle φ, which also means that the resulting fields for linear superposition of the TEM and a set of TE_{m1} modes can be expressed as a Fourier series. Different cross-sectional cuts of the field distribution in the coaxial waveguide are schematically shown in Fig. 5 for the exact analytical field solutions (see [4] and [5]).

B. Coupling Region

As input and output ports of the antenna p coaxial connectors (50 Ω) are placed in a plane around the outer conductor of the overmoded coaxial waveguide (Fig. 3). For coupling of

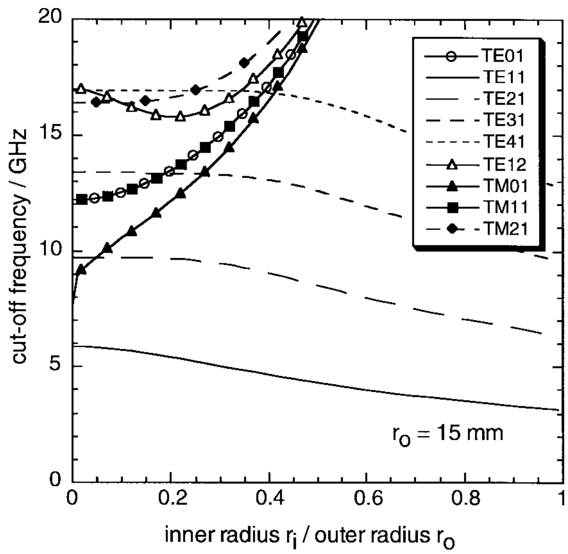


Fig. 4. Cutoff frequencies for the overmoded coaxial waveguide (mode chart).

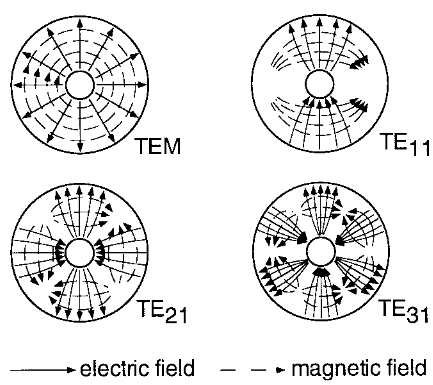


Fig. 5. Cross-sectional cuts of the field distributions in the coaxial waveguide.

the waveguide modes, capacitive stubs are used in this design although inductive coupling is possible as well. The design of the coupling region is assisted by numerical field simulations using finite-element frequency-domain (FEFD) algorithms [6]. As a result the S matrix for a $p+2$ port with $m+1$ modes is obtained, where p is the total number of coaxial feed connectors (Fig. 6) and m is the order of the highest TE_{m1} mode. Their S parameters describe the magnitudes and phases of the modes in the overmoded coaxial waveguide, the coupling between the feed connectors, and the reflection coefficients at the ports.

Because only one side of the overmoded coaxial waveguide is continued via the transition into the biconical waveguide, the other end must be terminated, either by an electric short or by an absorber (lower end in Fig. 3). An absorbing termination will absorb nearly half of the power coupled into the coaxial structure, whereas an electric short will reflect the waves to the coupling region. This can be used to control the ratios in which the modes are excited, as can be seen from the signal flow graph in Fig. 7. It has to be kept in mind that the different modes propagate at different velocities and, thus, limit the bandwidth. In practice, 2–12% are achievable. For better visualization only one input port is active while the others are

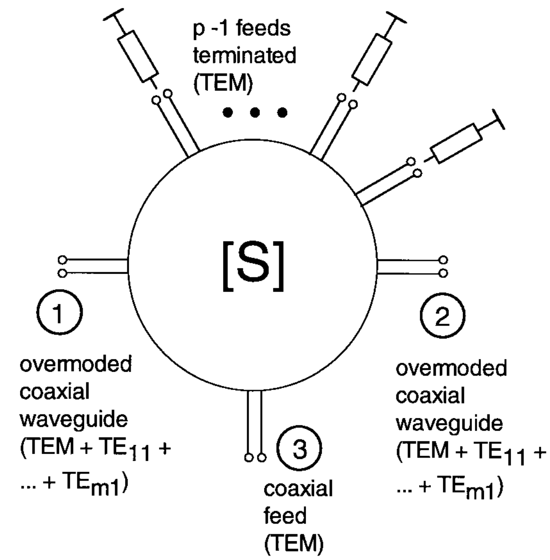


Fig. 6. Representation of the coupling zone as a $p+2$ port.

terminated with 50 Ω and only the signal flow for one mode is represented. Applying Mason's rule, transmission coefficients

$$T^m = \frac{b^m}{a} = S_{23}^m - S_{13}^m \cdot S_{21}^m \cdot \frac{e^{-j2k^m z_1}}{1 + S_{11}^m \cdot e^{-j2k^m z_1}} \qquad (1)$$

from the incident wave a at the active input (here at port 3) to the output waves b^0 and b^m of the TEM and TE_{m1} modes in the overmoded coaxial waveguide (here at port 2), respectively, can be calculated. They describe the complex amplitudes for the modes with index m propagating in the overmoded coaxial waveguide (with the propagation constant k^m), as a function of the location of the electric short z_1 (here at port 1).

C. Transition Between Coaxial and Biconical Waveguide

The set of electromagnetic modes excited in the coaxial waveguide (i.e., cylindrical coordinate system) has to be transformed into modes that satisfy Maxwell's equations in the biconical waveguide that is preferably described in spherical coordinates. It is important to state that the symmetry in azimuth direction is common for both coordinate systems, which means that the field solutions show the same dependence on the azimuth angle φ by harmonic functions. If this symmetry is maintained also in the transition, there is no modal coupling between modes with different azimuthal order m. Discontinuities in the transition can, however, result in the unwanted excitation of spherical TE_{mn} modes with an index $n > 0$. This should be avoided as these modes can disturb the vertical radiation pattern.

The transition geometry (as shown in Fig. 8) is developed empirically with satisfying results in numerical field simulations (FEFD) and in practical experiments. Compared with simulations of a similar structure described by Ess [7], this design produces less disturbance to the vertical radiation pattern. As the surfaces in this transition are no coordinate surfaces in any trivial coordinate system, the electromagnetic fields in this region cannot be determined easily by analytical calculations. The design procedure therefore uses the numerical results for

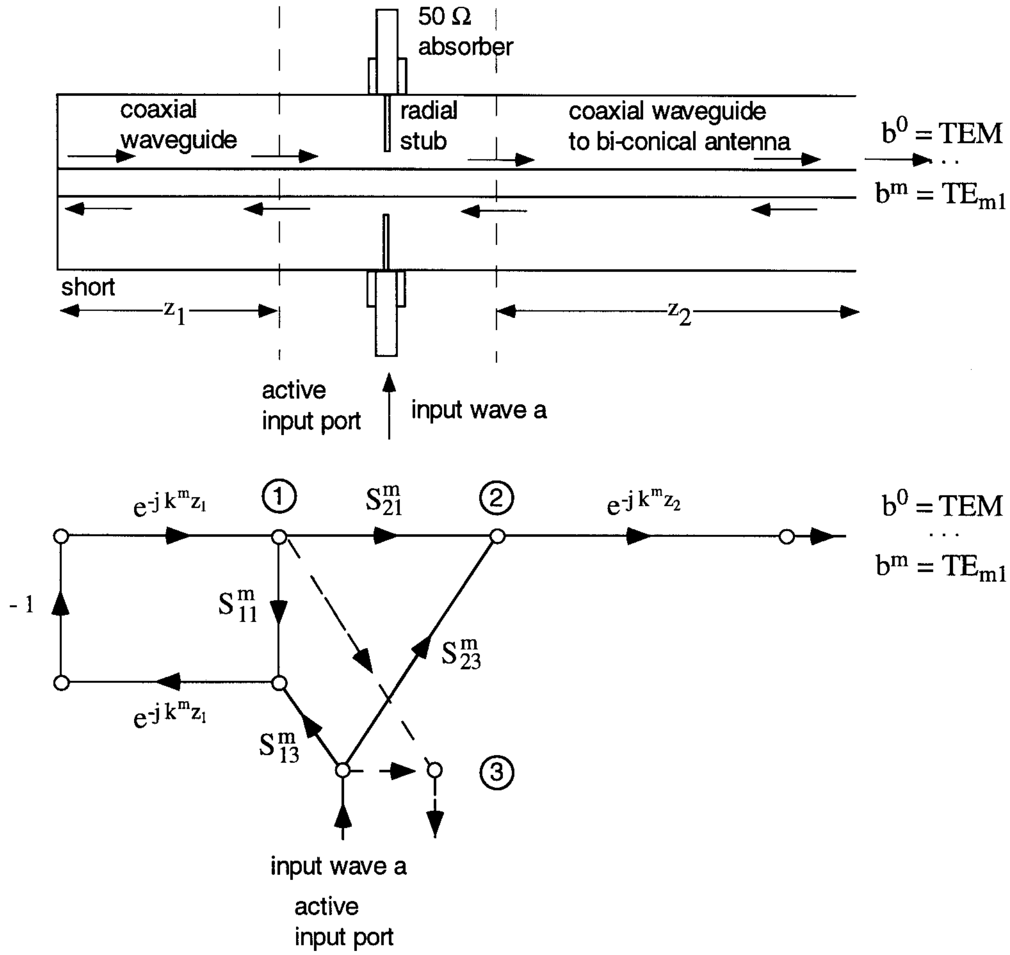


Fig. 7. Signal flow graph for the coupling region (simplified for one single mode and one feed active).

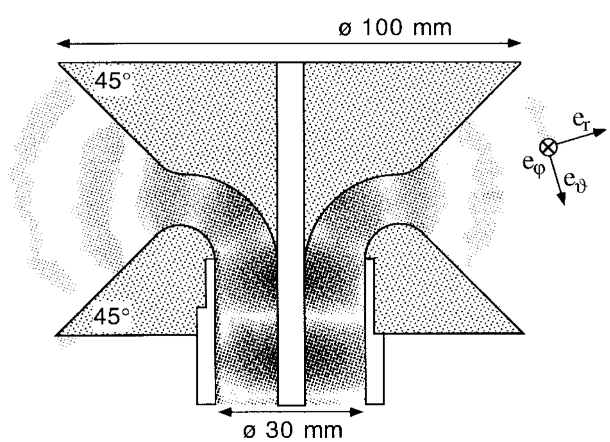


Fig. 8. Geometry of the transition zone from cylindrical to spherical coordinates (unit vectors e_i) and electric field intensities.

amplitude and phase of the conversion factors, which describe the transformation from cylindrical waves in the coaxial waveguide to spherical waves in the biconical waveguide.

D. Biconical Waveguide

The biconical waveguide allows the propagation of spherical waves, which satisfy the boundary conditions at the conical surfaces. In this waveguide TEM, TM, and TE modes are possible, all of which have no cutoff frequency. In our design, only TEM and TE_{m0} modes are fed, but due to mode conversion in the transition zone also TE_{mn} modes with $n > 0$ may be excited at reduced amplitude. The field solutions of the spherical modes and their derivation can be found, e.g., in [4] and [5]. For the calculation of the far-field radiation, only the components parallel to the radiating aperture (υ, φ-surfaces) are of importance (Schelkunoff's equivalence principle [8]).

E. Far-Field Radiation

For the calculation of the far-field radiation pattern, the tangential electric and magnetic fields in the radiating aperture are well known [4], [5]. Using a generalized form of Huygens' principle [8] allows the calculation of the far-field patterns in the direction $\upsilon_{RX}, \varphi_{RX}$. For the TEM mode, this was already shown in [9], where this method was used for studying the influence of the flare angles υ_1 and υ_2 of a biconical waveguide with cone length R on the vertical radiation pattern. The same method can be applied to spherical TE_{m0} modes, which allows in combination with the results for the TEM mode the calculation of the far-field azimuth and elevation patterns for any combination of TEM and TE_{m0} modes.

The idea of using an unsymmetric biconical waveguide in order to tilt the vertical radiation pattern upward or downward, as presented in [9], can also be used in the design of the multimode biconical antenna. For control of the elevation patterns, methods successfully applied to rectangular E-plane horn antennas are applicable as, for example, corrugations for the suppression of vertical sidelobes.

III. Antenna Pattern Synthesis for SDMA

The design procedure of the multimode biconical antenna (as described above) allows the excitation of a set of electromagnetic modes in the biconical waveguide, which produce horizontal far-field antenna patterns that are harmonic functions of the azimuth angle φ. Linear superposition of the modal electric and magnetic fields in the biconical waveguide enables the synthesis of the fields in the radiating aperture by a series of harmonic functions and, therefore, also of the horizontal radiation pattern.

A. Linear-Mode Superposition

For SDMA applications the multimode biconical antenna is equiped with several coaxial feed connectors distributed in azimuth direction. Each of them excites a number of modes for which the far-field radiation patterns add up for radiation in one single direction. Different azimuth directions can be addressed for transmitting or receiving by simply switching to another coaxial feed. Alternatively, several inputs can be used independently by multiple transmitters and receivers simultaneously.

Generally, the modes have to be excited with certain amplitudes, TEM with u_0, TE_{m1} with u_m, and v_m (with different azimuthal orientation, because of degeneration) so their linear superposition will lead to an antenna pattern

$$C(\varphi) = \left| u_0 + \sum_{m=1}^{M} u_m \cdot \cos(m\varphi) + v_m \cdot \sin(m\varphi) \right|. \qquad (2)$$

$C(\varphi)$ has to satisfy the requirements for a given application, e.g., beamwidth and sidelobe suppression.

Optimization algorithms can be applied for pattern synthesis, which fit the resulting antenna diagram into a tolerance scheme while minimizing a penalty function. Pattern synthesis is limited by the highest order M of the involved harmonic field functions, which can be increased for a fixed frequency only by enlarging the outer diameter of the overmoded coaxial waveguide. Antenna radiation patterns of a test design with eight feeds using TEM, TE_{11}, and TE_{21} modes are shown in Figs. 9 and 10. This antenna is designed for a frequency of 10.25 GHz with 15-mm outer radius r_o of the coaxial waveguide. With the above, given three modes, the resulting beamwidth is 85°, while the sidelobe suppression is -18 dB in the worst case.

B. Beam Rotation by Simple External Networks

Electronic beam rotation can be achieved easily by a modified design of the multimode biconical antenna in combination with a simple amplitude and phase-shifting network. An example for this special setup is given in Fig. 11. Power input at coaxial port A is coupled to the TEM mode, which radiates omnidirectionally in the horizontal plane. Ports B and C excite TE_{11} modes with an azimuthal offset of 90°. For the amplitudes at port A, u_1 at port B, and v_1 at port C, the relation

$$u_0 = \sqrt{u_1^2 + v_1^2} \qquad (3)$$

must be retained. The amplitudes u_1 and v_1 have to be varied for electronic beam steering; also, negative signs must be allowed for u_1 and v_1 (phase reversal of 180°). This can be implemented by using double-balanced modulators in the feed networks for u_1 and v_1. Linear superposition of the three modes results in a single-directional radiation pattern

$$C(\varphi) = |u_0 + u_1 \cdot \sin\varphi + v_1 \cdot \cos\varphi| \qquad (4)$$

with theoretically infinitely high forward/backward ratio. As only two modes are used in this example, the resulting beamwidth of 170° is very broad. It decreases if a higher number of modes is excited and it requires at the same time a higher number of input feed connectors and modulators.

C. Adaptive Antenna Patterns

The multimode biconical antenna can also be used in the same manner as an antenna array for adaptive antenna pattern implementation when combined with an electronically steerable amplitude and phase-shifting network. In communications

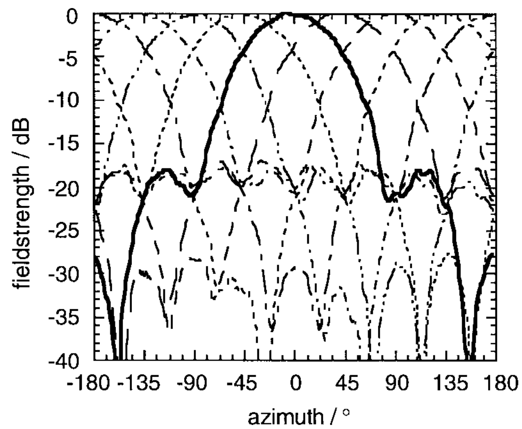


Fig. 9. Measured horizontal antenna patterns for SDMA using TEM, TE_{11}, and TE_{21} modes at 10.25 GHz.

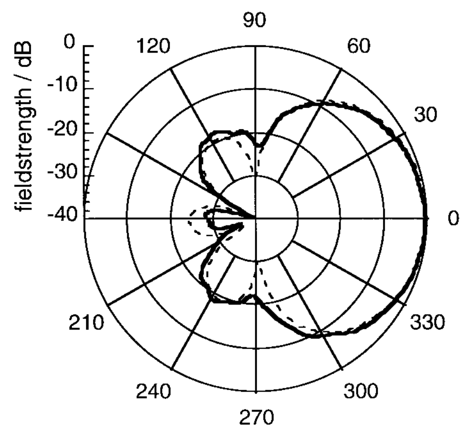


Fig. 10. Horizontal antenna pattern for one single active beam as measured (solid line) and calculated (dashed line). TEM, TE_{11}, and TE_{21} modes are used at 10.25 GHz.

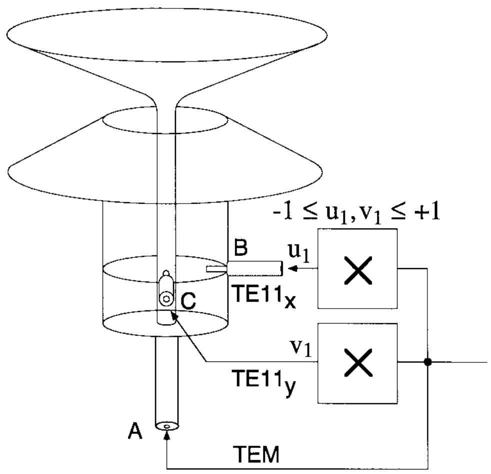


Fig. 11. Modified antenna design for electronic beam rotation.

with several coherent receiver modules, digital beamforming is possible. The multiple feed connectors replace the multiple antenna elements of the array and the same types of feed networks can be applied as for antenna arrays. Compared to adaptive antennas based on cylindrical arrays, mutual coupling between antenna elements is not a problem for pattern synthesis with the multibeam biconical antenna as all coupling effects are already included in the pattern for one single active input feed.

IV. Conclusion

In a new approach higher order modes are excited in a biconical horn antenna for directed radiation of electromagnetic waves. Linear superposition of TEM and TE_{m1} modes in the feeding coaxial waveguide enables the synthesis of the far-field radiation pattern in the horizontal plane, equivalent to the Fourier series expansion of a periodic function. Multiple feed connectors allow simple application of this antenna for SDMA as each connector results in an antenna diagram of the same shape but in a different angular direction. This can be achieved without the need for an external network.

When, however, an optional amplitude and phase-shifting network (e.g., implemented by double-balanced mixers) is added to the multiple feed connectors, the radiation pattern can also be steered electronically or adaptive antenna patterns can be implemented.

This antenna can be manufactured at very low cost as it contains no expensive parts or material. The polarization of the antenna, as presented here, is vertical arbitrary polarization and can be achieved by polarization filters. Because of its flexible design, the multimode biconical antenna can be used for many different applications at microwave frequencies such as mobile communication, direction finding, and directional communication.

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